A Novel Formulation of the Vehicle Routing Problem for Humanitarian Applications

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The United Nations Humanitarian Air Service (UNHAS) currently performs their flight planning by hand, resulting in possibly non optimal routing with little decision support. Research has mainly focused on commercial applications, leaving humanitarian applications underexposed. This study aims at improving the efficiency and effectiveness of flight routing and scheduling in a humanitarian setting by creating a linear programming model. A novel, airport-based, formulation of the vehicle routing problem is presented. Based on this formulation a model is created that also incorporated the monthly minimum guaranteed flight hours per aircraft. The results of this model are compared to human flight planners and a reference model. When considering day-to-day optimization, the model realized cost savings of 4.6% till 10.5% with respect to the human flight planners and 1.8% compared to a reference model. When considering the minimum guaranteed hours, the model obtained solutions that were 4% cheaper compared to the daily optimization mode and 1.6% compared to the human flight planner. Furthermore, analyses were performed that offer insight in the effect of the contract structure on the operational costs.

I. Nomenclature

Constants

- $[a_p^r, b_p^r]$: time window for the pickup of request r
- $[a_d^r, b_d^r]$: time window for the delivery of request r
- B_n: cummulated flight hour budget for day n
- c_{ij}^k: cost of vehicle k traversing arc (i, j)
- d_{ij}: distance between node i and j
- D^r: delivery location of request r with $D^r \in N^-$
- mgh: minimum guaranteed hours
- P^r: pickup location of request r with $P^r \in N^-$
- q_{req}^r: number of passengers from request r
- Q^k: capacity of vehicle k
- ra^k: range of vehicle k
- s_i: service time (TAT) at node i
- t_{ij}^k: travel time of vehicle k of arc (i, j)
- Δ_t: required time difference between landings or departures
- Π^r: penalty cost of spilling a passenger from request r

Sets

- A^k: set of arcs (i, j), $(V^{+k} \times V^{+k} \mid i \neq j)$, for vehicle k
- E_i: set of potential revisits for airport i for $i \in N^-$
- K: set of vehicles
- N^{-k}: set of airports compatible with vehicle k
- N^{+k}: set of airports and depots compatible with vehicle k
- R: set of requests
- V^{-k}: set of airports incl. potential revisits compatible with vehicle k
- V^{+k}: set of airports incl. potential revisits and depots compatible with vehicle k
- V_{fuel}: set of airports with refueling possibilities

Decision variables

- ${q_p}_i^{rk}$: amount of passengers from request r picked up at node i by vehicle k
- ${q_d}_i^{rk}$: amount of passengers from request r delivered at node i by vehicle k
- u_i^k: load of vehicle k after node i
- v_i^k: distance traveled by vehicle k (since refueling) when arriving at at node i
- ${w_a}_i^k$: time of arrival at node i by vehicle k
- ${w_d}_i^k$: time of departure from node i by vehicle k
- x_{ij}^k: binary, 1 if arc (i, j) is traversed by vehicle k
- ${y_p}_i^{rk}$: binary, 1 if (part of) request r is picked up at node i by vehicle k
- ${y_d}_i^{rk}$: binary, 1 if (part of) request r is delivered at node i by vehicle k

II. Introduction

The main research objective of this paper is:

To improve the efficiency and effectiveness of flight routing and scheduling in a humanitarian setting taking into account the operational and safety constraints specific to non-commercial humanitarian air transport by creating a linear programming model

The related research questions are the following:

- What is the state-of-the-art in vehicle routing with pickup and delivery?
- Can the efficiency of the model be further improved by simplifying the formulation regarding the pickup and delivery nodes?
- Can the model be further improved by optimizing while considering the monthly minimum guaranteed hours?

Section III provides the reader with background on UNHAS operations and relevant literature. A novel formulation of the vehicle routing problem is introduced in Section IV. In Section V, the model is further described. The results of the model can be found in Section VI. Verification, validation and multiple sensitivity analyses are discussed in Section VII. Finally, the conclusions and recommendations are presented in Section VIII.

III. Background

This section provides context for the executed research. Background on the case study at hand can be found in Section III.A. An overview of the relevant literature is discussed in Section III.B.

A. UNHAS South Sudan

The United Nations Humanitarian Air Service (UNHAS) is the central air service for the United Nations and managed by the World Food Programme (WFP) [24]. It is used by the entire humanitarian and development community, and enables access to locations that are hard to reach due to conflict, natural disasters or missing infrastructure. UNHAS is active in 16 countries, creating a network of 323 regular destinations with a fleet of over 60 aircraft. In 2018, 386,330 passengers were transported by UNHAS, consisting for 55% of NGOs, 40% United Nations and 5% donors, diplomats and other users [24].

From the countries where UNHAS is active, South Sudan is the largest when it comes to transported passengers (ca. 98,500 passengers in 2018 [24]). This makes it the most suitable country to use as a case study: if the model performs well for South Sudan it is likely that it will perform satisfactorily in the other countries where less passengers are transported.

Since UNHAS has humanitarian goals, the routing focuses on maximization of demand satisfaction while staying within budget (cost minimization). This is fundamentally different from commercial airlines, which focus on profit maximization. This makes existing routing models developed for this purpose inadequate. Furthermore, UNHAS operations are characterized by highly irregular requests. Therefore, a new flight routing schedule is constructed each day for the next day. This is currently done by hand, which makes the process time consuming, potentially inconsistent and nontransparent without guaranteeing an optimal solution. An automated model could offer time savings, cost savings, higher demand satisfaction and improved decision support. Such a model should incorporate the following aspects:

1) **Daily changing O-D demand**: the demand in pickups and deliveries changes daily and needs to be flexible to unexpected input. Therefore, schedules have to be made 48-24 hours before departure.
2) **Maximum flight time and minimum turnaround time:** each aircraft can fly a maximum of 10 hours per day, with a minimum of 20 minutes ground time. All aircraft must start and end at their hub.
3) **Operational constraints of the aircraft and airports:** each aircraft has certain specifications that must be considered (such as range, capacity etc), also in combination with the airport specifications (such as runway length).
4) **Multiple stop flights:** the aircraft must make multiple stops per flight to allow the passengers to board and deboard.
5) **Monthly aircraft utilization:** the aircraft are wet leased by UNHAS, where the contract dictates a minimum amount of block hours per month per aircraft of 60. This cost structure should be considered when planning the routes.
6) **Fifteen minute take-off difference:** for safe operations two aircraft departing from the same airport should be separated by a quarter of an hour

B. Literature review

Section III.B.1 gives a brief overview of relevant literature to this research and Section III.B.2 discusses the literature gap.

1. State of the Art

The United Nations flight routing problem is known in literature as the vehicle routing problem, specifically a multi-depot heterogeneous pickup and delivery problem with time windows [19]. The vehicle routing problem (VRP) has been studied quite intensively over the past 60 years [16].

The VRP is a generalization of the Traveling Salesman Problem (TSP) and is therefore NP-hard [5]. The TSP can be described as follows: a salesman has to visit multiple markets while starting and ending at his home town and minimizing the traveled distance. An overview of exact and approximate solving methods can be found in [15].

The VRP extends on the concept of the TSP by replacing the salesman by a (heterogeneous) fleet (see [10], [17] and [22]), adding time windows (see [5] and [8]), adding multiple depots (see [18] and [9]), adding pickups and deliveries (see [21], [11] and [13]) or considering multiple periods (see [4] and [23]). An extensive overview of different versions of the VRP is provided by [12] and [6].

Regarding the solving method for these different versions of the VRP, three main categories exist: exact algorithm, heuristics and metaheuristics. Classical heuristic are defined as heuristics that do not allow the intermediate solution to decline during the algorithm, while metaheuristics do allow this [16]. In other words: heuristics get trapped in local optima, while metaheuristics can move out. A comprehensive overview of different solving methods for the VRP is provided by [16].

A solution to the UNHAS South Sudan case is proposed by [19]. Using a formulation based on [20] and commercial solvers based on branch and cut algorithms (like CPLEX [1] and Gurobi [2]), results were produced that were around 77% faster and 2 till 8% more cost effective than current manual planning. It was found that CPLEX slightly outperformed Gurobi for the UNHAS case.

2. Literature Gap

Both the formulation proposed by [19] and other formulation found in literature define a network where each request consists of a pickup node and a delivery node. When multiple requests use the same airport this results in multiple nodes describing the same physical location. Especially in a scenario like the UNHAS South Sudan case, where most requests originate or end at the hub, this causes an unnecessary large problem formulation. For example, a given day in the UNHAS data consists of 31 requests containing 15 airports. The request-based formulation would require 62 nodes (2 per request). The amount of arcs between N nodes equals $N(N-1)$ [15], meaning around 3800 arcs are required. If a formulation existed where the nodes represent the physical locations, only 15 nodes would be required, amounting to 210 arcs. The amount of arcs is not the only driver for the size of the problem formulation, but it is evident from this (simplified) example that an alternative formulation could be beneficial.

Additionally, UNHAS needs to consider the minimum guaranteed hours for each aircraft. Rolling horizon planning is impracticable, since requests are irregular and only known a few days prior to departure. A method is required that considers the minimum guaranteed hours, with only the requests information available for the current and past days.

Both an airport-based node formulation and a method for considering minimum guaranteed flight hours have not been found in literature, indicating a literature gap that this research can address.

IV. Novel Formulation of the Linear Program

As stated in Section III.B.2 all formulations found in literature are potentially unnecessarily large if many requests utilize the same airports. This is the case for the UNHAS operations, but also for many other applications that rely on hub-based operations.

Therefore, a new formulation was developed based on the concept of creating one node per airport. However, since a (visited) node represents a point in space and a point in time some nodes still need to be duplicated to allow multiple visits of the same airport. In practice, this is only required for the hub airports and refueling airports. The novel mathematical formulation of the linear program is described in Eqs. 1 till 23. The nomenclature can be found in Section I.

The objective function is given by Eq. 1 and consists of two parts. The first part consist of the cost of the chosen route and the right part is a spillage penalty. These two parts of the objective function represent the two goals of the flight planning: cost minimization and demand satisfaction maximization. Constraint 3 ensures vehicle flow. Constraints 4 and 5 describe that only pickups or deliveries can be made if the node is visited. If no pickup or delivery is made, the pickup or deliver quantity should be zero, as stated in Constraints 6 and 7. Constraints 8 and 9 ensure only pickups or deliveries are made at nodes that are a pickup location or delivery location. Pickup and delivery amount consistency per request is described by Constraint 10, and vehicle consistency per pickup and delivery is enforced through Constraint 11.

Constraints 12 and 13 describe the load of the aircraft and ensure capacity is respected. Travel times and turn around times are described in Constraints 14 and 15, respectively. These constraints also eliminate subtours [11]. The time windows for transit passengers are enforced through Constraints 16 and 17, and Constraint 18 ensures that pickup takes place before delivery. To guarantee enough time is scheduled between aircraft arriving or departing from the same airport, Constraints 19 and 20 were added. Constraints 21 till 23 ensure range criteria are met, with Constraint 22 describing the situation where refueling takes place.

Constraints 4 till 7, 12, 14, 16 till 22 are strictly speaking not linear. It is possible to linearize these constraints using big M methods [7]. However, commercial solvers like CPLEX can incorporate these kind of formulations in the branching process, providing more efficient results than big M methods [14].

$$\text{min:} \sum_{k\in K} \sum_{(i,j)\in A^k} c_{ij}^k x_{ij}^k + \sum_{r\in R} \Pi^r \left(q_{req}^r - \sum_{k\in K} \sum_{i\in V^{+k}} q_{p_i}^{rk} \right) \tag{1}$$

$$\text{subject to:} \tag{2}$$

$$\sum_{j:(i,j)\in A^k} x_{ij}^k - x_{ji}^k = \begin{cases} 1 & \text{if } i \text{ is start depot} \\ -1 & \text{if } i \text{ is end depot} \\ 0 & \text{otherwise} \end{cases} \qquad \forall k \in K,\ \forall i \in V^{+k} \tag{3}$$

$$\text{if } y_{p_i}^{rk} = 1: \quad \sum_{j:(j,i)\in A^k} x_{ji}^k = 1 \qquad \forall k \in K,\ \forall r \in R,\ \forall i \in V^{+k} \tag{4}$$

$$\text{if } y_{d_i}^{rk} = 1: \quad \sum_{j:(j,i)\in A^k} x_{ji}^k = 1 \qquad \forall k \in K,\ \forall r \in R,\ \forall i \in V^{+k} \tag{5}$$

$$\text{if } y_{p_i}^{rk} = 0: \quad q_{p_i}^{rk} = 0 \qquad \forall r \in R,\ \forall k \in K,\ \forall i \in V^{+k} \tag{6}$$

$$\text{if } y_{d_i}^{rk} = 0: \quad q_{d_i}^{rk} = 0 \qquad \forall r \in R,\ \forall k \in K,\ \forall i \in V^{+k} \tag{7}$$

$$y_{p_i}^{rk} = 0 \qquad \forall k \in K,\ \forall r \in R,\ \forall i \in V^{+k} \setminus E_{P^r} \tag{8}$$

$$y_{d_i}^{rk} = 0 \qquad \forall k \in K,\ \forall r \in R,\ \forall i \in V^{+k} \setminus E_{D^r} \tag{9}$$

$$\sum_{k\in K} \sum_{i\in V^{+k}} q_{p_i}^{rk} \le q_{req}^r \qquad \forall r \in R \tag{10}$$

$$\sum_{i\in V^{+k}} q_{p_i}^{rk} = \sum_{i\in V^{+k}} q_{d_i}^{rk} \qquad \forall k \in K,\ \forall r \in R \tag{11}$$

$$\text{if } x_{ij}^k = 1: \quad u_j^k \ge u_i^k + \sum_{r\in R} (q_{p_j}^{rk} - q_{d_j}^{rk}) \qquad \forall k \in K,\ \forall (i,j) \in A^k \tag{12}$$

$$u_i^k \le Q^k \qquad \forall i \in V^+,\ \forall k \in K \tag{13}$$

$$\text{if } x_{ij}^k = 1: \quad w_{a_j}^k \ge w_{d_i}^k + t_{ij}^k \qquad \forall (i,j) \in A^k,\ \forall k \in K \tag{14}$$

$$w_{d_i}^k \ge w_{a_i}^k + s_i \qquad \forall k \in K,\ \forall i \in V^{+k} \tag{15}$$

$$\text{if } y_{p_i}^{rk} = 1: \quad a_p^r \le w_{d_i}^k \le b_p^r \qquad \forall r \in R,\ \forall k \in K,\ \forall i \in V^{+k} \tag{16}$$

$$\text{if } y_{d_i}^{rk} = 1: \quad a_d^r \le w_{a_i}^k \le b_d^r \qquad \forall r \in R,\ \forall k \in K,\ \forall i \in V^{+k} \tag{17}$$

$$\text{if } y_{p_i}^{rk} = y_{d_j}^{rk} = 1: \quad w_{d_i}^k \le w_{a_j}^k \qquad \forall r \in R,\ \forall (i,j) \in A^k,\ \forall k \in K \tag{18}$$

$$\text{if } \sum_{n:(in)\in A^{k_1}} x_{in}^{k_2} = \sum_{n:(jn)\in A^{k_2}} x_{jn}^{k_2} = 1: \quad |w_{d_i}^{k_1} - w_{d_j}^{k_2}| \ge \Delta_t \qquad \forall k_1, k_2 \in K \mid k_1 \ne k_2,\ \forall i \in V^{+k},\ \forall j \in E_i \tag{19}$$

$$\text{if } \sum_{n:(ni)\in A^{k_1}} x_{ni}^{k_2} = \sum_{n:(nj)\in A^{k_2}} x_{nj}^{k_2} = 1: \quad |w_{a_i}^{k_1} - w_{a_j}^{k_2}| \ge \Delta_t \qquad \forall k_1, k_2 \in K \mid k_1 \ne k_2,\ \forall i \in V^{+k},\ \forall j \in E_i \tag{20}$$

$$\text{if } x_{ij}^k = 1: \quad v_j^k \ge v_i^k + d_{ij} \qquad \forall k \in K,\ \forall (i,j) \in A^k,\ \text{if } i \notin V_{fuel} \tag{21}$$

$$\text{if } x_{ij}^k = 1: \quad v_j^k \ge d_{ij} \qquad \forall k \in K,\ \forall (i,j) \in A^k,\ \text{if } i \in V_{fuel} \tag{22}$$

$$v_i^k \le ra^k \qquad \forall k \in K, \forall i \in V^{+k} \tag{23}$$

V. Model

To solve the UNHAS South Sudan case the formulation of the linear program as presented in IV was translated to a computer model. CPLEX [1] was used as optimization engine, combined with the Python [3] API DOcplex.

To ensure the model provides solutions of sufficient quality in a reasonable amount of time on a regular computer it was further adapted. These adaptations were aimed at improving convergence and consisted of two main strategies: reducing the number of decision variables and reducing the solution space by adding constraints.

A. Division Heuristic

When a problem is too large to solve within a practical time limit, it can be divided in several smaller sub-problems. This is the case for UNHAS South Sudan. A division in regions for South Sudan was proposed by [19], based on expert planners input for 2015. Since the fleet composition and destinations served changed for 2019 (the year this research focuses on) the region division was revised, again using expert input. The new region division can be found in Appendix A, Figure 10. Some dynamic elements were added to the region division, which Appendix A further elaborates on.

The different regions are solved one by one. The solutions of the different regions are dependent, meaning the solution from the previous region affects the solution for the next region (fleet availability and transit times are the main reasons for this). This makes the order of solving the regions of importance to the final solution. The following solution order is proposed:

1) The Rumbek and Wau region are solved
2) The Juba West region is solved
3) The Juba East region is solved (if it has transit passengers)
4) The other regions are solved sorted from many to few requests

This order is based on solving the regions with transit passengers first, and solving the hard regions with many requests first. It is chosen to solve the Rumbek and Wau region before the Juba West region because of the high level of predictability of the Juba West region route. This is illustrated in Figure 1.

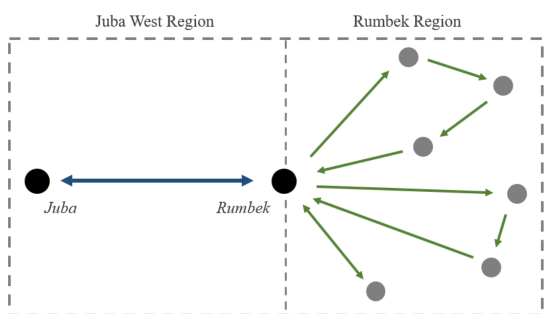

Fig. 1 Schematic overview of transit passengers, motivating the order in which the regions are solved.

This division heuristic, although effective in reducing the computational time, has some limitations. Firstly, a global optimum might be missed, since this optimum can comprise of routes between different regions. Furthermore, an optimum might be missed since the routes are solved one by one. The model may choose a solution for the first region that has negative consequences for a region that is solved later.

B. Filtering

To reduce the amount of arcs (i, j) and therefore the amount of decision variables x^k_{ij}, the following arcs were removed:

- Arcs ending or starting at an airport with a smaller runway than required by vehicle k
- Arcs with a distance larger than the range of vehicle k
- Arcs starting at the end-hub or ending at the start-hub of vehicle k
- Arcs starting at the start-hub and ending at an airport where only a delivery can be made
- Arcs starting at an airport where only a pickup can be made and ending at the end-hub
- Arcs not starting or ending at one of the airports in Table 15 if vehicle k is a helicopter

Most of these filtering techniques are obvious and generally applicable to any problem. However, the last item is specific to the South Sudan case and requires further elaboration. The helicopters are the most expensive vehicles in the fleet. Although they can land on any airport, it is unlikely that an optimal route consists of a helicopter flying towards an airport where an airplane can land as well. Therefore only airports that can only accommodate helicopters and a few other airports close to these airports were added to the set of compatible airports N^{-k} for helicopters.

C. Auxiliary Constraints

To limit the solution space, several auxiliary constraints were added to the model. Some of these constraints alter the problem formulations (Appx. C, Eq. 26 till 33), meaning they could possibly make an optimal solution infeasible. Other auxiliary constraints (Appx. C, Eq. 34 till 43) are merely a mathematical consequence of the other constraints, and can therefore be considered as cuts. An overview of all auxiliary constraints can be found in Appendix C. Described in words, the following constraints were added that alter the problem formulation:

- Visiting times ordering of the potential revisits (Appx. C, Eq. 26)
- Flight time priority (or ordering) of aircraft of the same type (Appx. C, Eq. 27)
- The Dash Q must be used in the Juba West region (Appx. C, Eq. 28)
- The maximum number of legs per route equals five (Appx. C, Eq. 29)
- Per request an aircraft makes a maximum of 1 pickup and 1 delivery (Appx. C, Eq. 30 and 31)
- Each request can be handled by a maximum of 6 aircraft (Appx. C, Eq. 32 and 33)

All of these auxiliary constraints are generally applicable to any case, except for the Dash Q constraint (Appx. C, Eq. 28). This constraint is specific to the UNHAS South Sudan case. The Dash Q is the largest aircraft in the fleet and can only land at a few airports. By forcing the use of the Dash Q in the Juba West region (where most of these compatible airports are), other aircraft remain free to be planned in other regions where the Dash Q cannot be used. In some instances, this tactic will lead to higher costs than necessary, since the large, expensive Dash Q must be used instead of a smaller cheaper aircraft.

D. Penalization

To reflect several considerations and further improve the convergence of the model, several penalization factors were added to the objective function. This helps the model to distinguish between similar solutions.

For example, a route (consisting of 3 or more legs) can be flown in two directions. In many cases, both solutions are equally suitable to become the planned route. To aid the model, a penalty is added to the objective function related to the amount of passengers transported on the first leg. This way, the model prefers the route that has the least amount of passengers on the first leg. This improves the convergence of the model, but also reflects a real world consideration. The amount of fuel on board is the highest at the start; therefore, it is preferred that the amount of passengers at the start is the lowest. The following penalties were added (see Appx. D, Eq. 45 till 50):

- Penalty for spilled passengers
- Penalty for passengers on the first leg (to distinguish between clockwise and counterclockwise routes)
- Penalty if the fleet order constraint is not adhered to (to distinguish between similar aircraft - see Appx. C, Eq. 27)
- Penalty for the final arrival time of all aircraft (to ensure a tight schedule)
- Penalty if refueling in Malakal is used (to reflect the higher fuel prices at this airport)
- Penalty if the Dash Q is not used in the Juba West Region (to ensure availability of other aircraft for other regions - see Appx. C, Eq. 28)

E. Monthly Optimization

As described in Section III.A, the monthly aircraft utilization should be considered when planning the routes. Each aircraft has a monthly minimum guaranteed amount of 60 flight hours. When optimizing the routing on a day-to-day basis it is plausible that one aircraft is used more than the monthly minimum, and another aircraft is used less. In this case, extra hours need to be paid for the first aircraft for overtime, and for the second aircraft the minimum still needs to be paid. It is evident that, on a monthly basis, it is more cost-effective to ensure the utilization for each aircraft is close to the minimum guaranteed flight hours.

In the ideal situation, the flight schedule for the full month would be made in one go, while minimizing overtime. However, this is not possible due to the irregular nature of the requests: for each day a flight plan needs to be constructed that considers the monthly flight hours, while only the flight hours of the previous days of the month are available and the requests for that day.

The proposed solution consists of the fleet order constraint (see Section V.C) and dynamic pricing. The fleet order constraint was adapted to prioritize aircraft that utilized less flight hours than the other aircraft of the same type. Through dynamic pricing, aircraft with lower utilization were preferred compared to all other aircraft. This was done using the cumulated flight hours per month. A budget was assigned that increased each day, and the cost of an aircraft differed depending on how much of the budget was already utilized. Figure 2 shows how the cost differ (as a percentage of the original cost) depending on how much of the budget is utilized (as percentage of the cumulated flight hours). The budget for each day n, for $0 \leq n \leq 20$, is calculated using Equation 24. This budget starts relatively high and tightens towards the end. This corresponds to the increased certainty near the end of the month. It is evident that aircraft that are underutilized become much cheaper than aircraft that reached their budget, making the distribution of the flight hours between the aircraft more even.

$$B_n = 6 + n \cdot \frac{mgh - 6}{20} \tag{24}$$

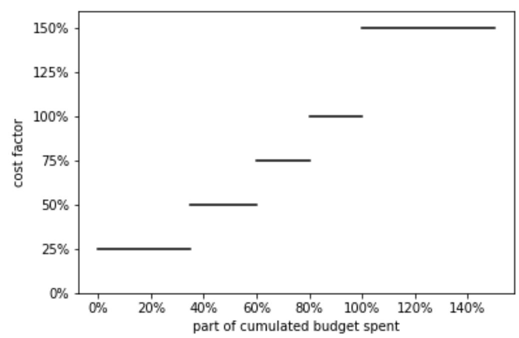

Fig. 2 Dynamic pricing scheme used for monthly optimization.

F. Normalization of the Objective Function

In order to properly combine the (dynamic) routing cost with the different penalty functions, each part was normalized and assigned a weight. This ensures that the model behaves suitably for different inputs. One of the most applied normalization techniques is to divide the function value minus the minimum value by the difference between the maximum and minimum function value (this leads to a normalized value in range $[0, 1]$). Since the minimum of all separate function values is zero in this case, it is only necessary to provide an estimate of the maximum function value. This leads to an objective function as described in Equation 25. Appendix D gives an overview of the different functions and the proposed (estimate of the) maximum values. Based on importance of the different penalty functions and an iterative assessment of the model results and speed, weights μ_n were assigned to each function, which can also be found in Appendix D.

$$\text{min:} \sum_{0 \leq n \leq 6} \mu_n \frac{f_n}{f_{n_{max}}} \tag{25}$$

G. Pareto Front Creation

For each day a Pareto Front should be created to offer decision support. Since two conflicting objectives are minimized (costs and number of passengers spilled) no single optimum exists. Instead, for each day, several points can be constructed that have Pareto optimality, meaning neither of the objectives (cost or passengers spilled) can be improved without deteriorating the other. It is up to a decision maker to select the route that best reflects this trade-off between passengers spilled and costs. Having access to the specific Pareto front of a given day gives the desired insight to make this choice.

Since the routing is divided into multiple regions, the final solution will be an addition of these separate solutions. This means that it is possible to construct the Pareto front by combining solutions in such a way that the cost for a given amount of spilled passengers is minimized. This was achieved by solving each region multiple times, while forcing a certain number of spilled passengers for each run. However, the solutions of the multiple regions are not independent, due to fleet availability, runway availability and transit times. It was chosen to use the solution with zero spilled passengers as the starting point for the next regions, as is schematically shown in Figure 3. When solving the region with different amount of passengers spilled, the previously found solution can be used as a starting point to save computational time. This concept is known as a warm start. For this model, a time limit of two hours was selected for the first time a region was solved (upper row in Figure 3), and a time limit of 10 minutes for the subsequent solves of the same region.

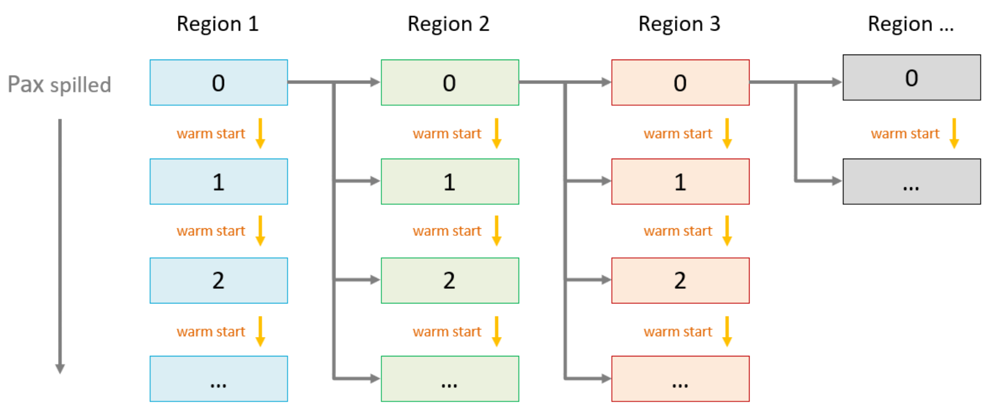

Fig. 3 Schematic representation of the construction of the different solutions to the regions that are combined to the Pareto fronts.

This approach has some limitations. Since the solution with zero passengers spilled is used as a starting point, any combination where a different amount of spilled passengers is selected is, therefore, not guaranteed to seamlessly fit regarding fleet availability, runway availability or transit times. Section VII.A.1 further assesses and quantifies these limitations.

VI. Results

The model as described in Section V was used on a data set of 11 days of UNHAS requests from 2019. The data set can be found in Appendix B. These flight routes were optimized per day as presented in Section VI.A. In line with Section V.E the flight routes were also optimized while considering the minimum guaranteed hours, which is presented in Section VI.B.

A. Daily Optimization

Pareto fronts were created for each day of the 2019 data set. As a reference point, the routes were optimized without considering the minimum guaranteed hours. The eleven Pareto fronts can be found in Appendix E.A. Table 1 provides an overview of the results. Figure 4 shows the cumulated flight hours per aircraft for comparison with the monthly optimization results,

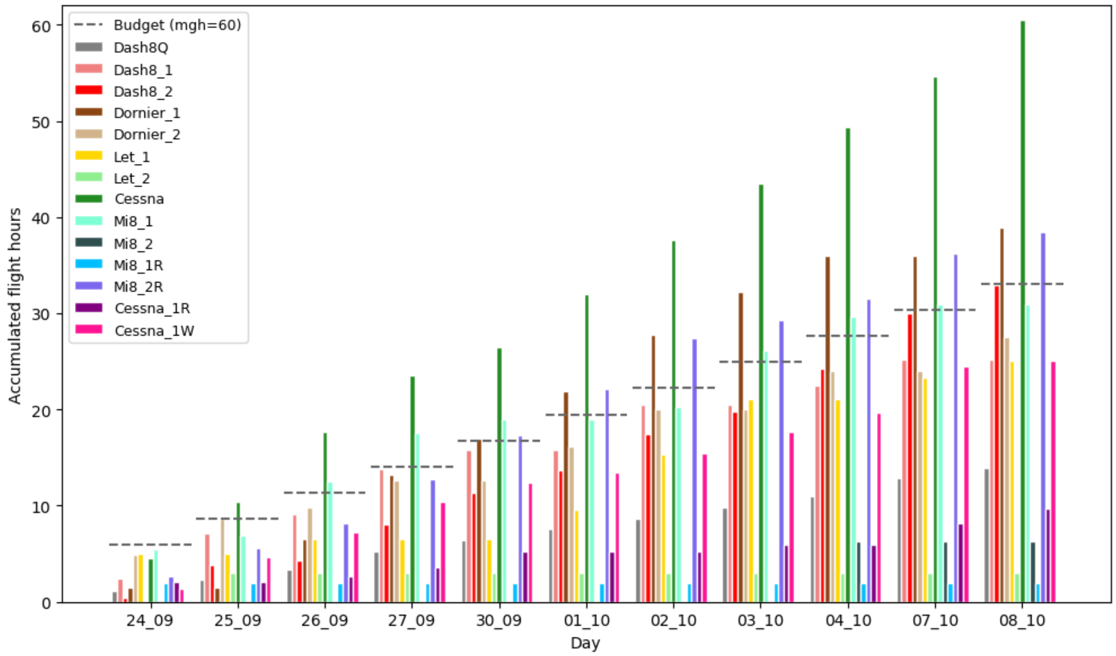

Fig. 4 Accumulated flight hours per aircraft. Daily optimization and 100% demand satisfaction.

Table 1 Comparison of the results for daily optimization and monthly optimization for the 2019 data. The costs as presented in this table do not consider the minimum guaranteed hours.

			Daily optimization		*Monthly optimization*	
Day	**#Requests**	**#Pax**	**Block hour cost [-]** *0 pax spilled*	**Time [hr]**	**Block hour cost [-]** *0 pax spilled*	**Time [hr]**
24-09	55	298	81,253	5.49	84,925	8.33
25-09	35	370	70,694	3.71	88,878	3.76
26-09	43	281	68,964	4.39	74,740	2.41
27-09	58	561	98,234	10.00	101,126	9.79
30-09	25	302	55,085	0.34	60,181	0.19
01-10	42	259	61,077	1.21	65,108	1.33
02-10	43	451	95.531	7.21	114,073	6.36
03-10	38	254	69,466	3.17	72,141	3.28
04-10	28	379	91,766	3.40	98,099	3.08
07-10	39	454	72,495	4.21	75,754	3.84
08-10	37	239	50,075	0.41	51,709	0.29
Total	443	3,848	814,057	43.54	885,979	42.66

B. Monthly Optimization

To account for the structure of the wet lease contracts from UNHAS, the minimum guaranteed hours were incorporated in the model as described in Section V.E. The contracts consists of 60 guaranteed flight hours per aircraft per month. The Pareto fronts and the flight routes considering 60 guaranteed hours can be found in Appendix E.B. Figure 5 shows the cumulated flight hours per aircraft, and Table 1 gives an overview of the cost and computation time. It can be seen that, without considering the contract structure, the monthly optimization produces more expensive routes.

However, when looking at Table 2 it can be seen that the monthly optimization saves 4% costs when the minimum guaranteed hours are accounted for. In this table, the block hour costs simply consist of the amount of flight hours multiplied by the cost, whereas the contract cost also consists of the cost to reach the minimum guaranteed hours for each aircraft. When running the model with the monthly optimization setting, sometimes more expensive aircraft are chosen to prevent overtime of other aircraft. Therefore the block hour costs are higher, whereas the contract costs are lower in this case.

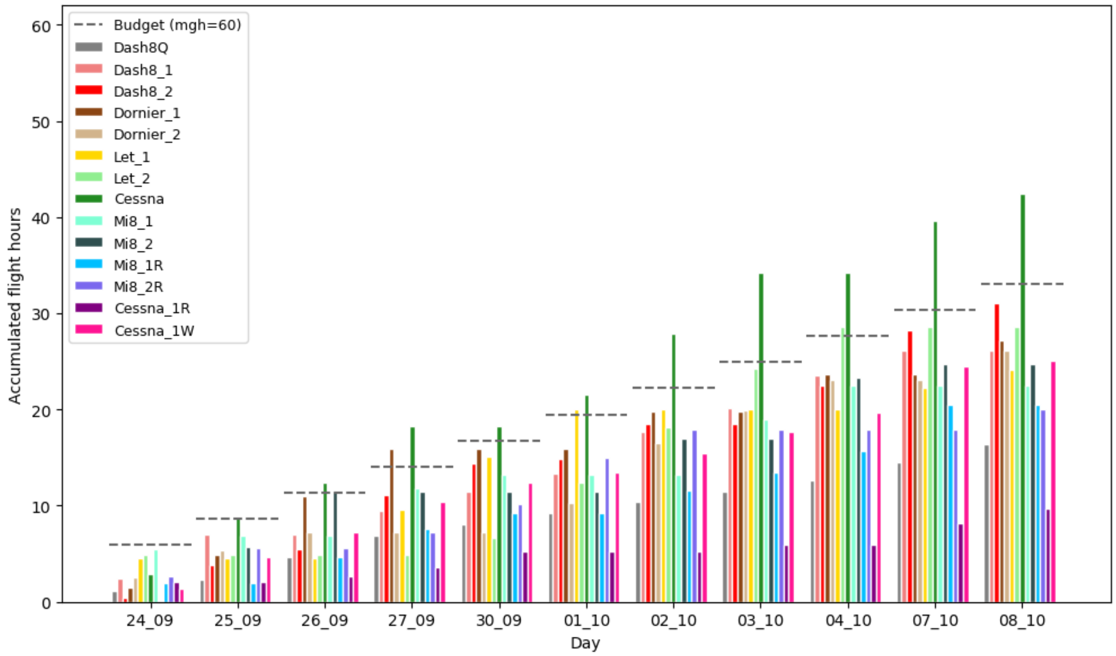

Fig. 5 Accumulated flight hours per aircraft. Monthly optimization (mgh=60) and 100% demand satisfaction.

Table 2 Comparison of the costs of optimizing per day or per month, with or without considering the 60 minimum guaranteed hours.

	Block hour cost [-]	**Contract cost [-]** *mgh=60*
Daily optimization	814,057	1,302,078
Monthly optimization	885,979	1,252,581
	+8.1%	-4.0%

VII. Verification & Validation

To analyze the behavior of the model verification (Section VII.A), validation (Section VII.B) and sensitivity analyses (Section VII.C) were performed.

A. Verification

The model was verified by running nine straightforward test cases. An elaborate description of the verification can be found in Appendix G. Also the method of creating the Pareto Fronts was verified, which is described in Section VII.A.1.

1. Pareto Front Verification

As described in Section V.G, the Pareto front is created by combining solutions, with varying demand satisfaction, from the different regions. However, since most of these solutions are dependent on the solutions of the other regions, it is not guaranteed that any combination is fully feasible. To quantify this limitation, reruns were performed where for each point on the Pareto front the regions were solved sequentially with the right amount of spilled passengers. Figure 6 gives a schematic visualization of how these reruns were performed, compared to the original Pareto front creation as schematically shown in Figure 3.

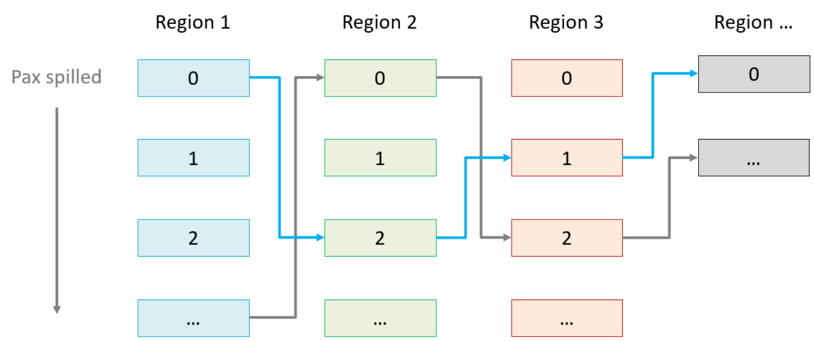

Fig. 6 Schematic representation of the verification of the construction of the Pareto fronts.

Appendix H shows the results of the verification reruns to the initial Pareto front. For a few days, these results are just as expected: a perfect match for the point with 0 passengers spilled, and maybe some small deviations for the points with more passengers spilled. This is the case for 24-09, 26-09, 30-09, 04-10 and 08-10. For a few days, the first point created by the reruns is different from that of the initial front (25-09, 27-09, 02-10). This means that within the given time limit the rerun found a different solution than the initial run. This indicates that the convergence is not always constant. Perhaps background application or room temperature have an effect on the performance of the computer, and therefore the results. In other instances, solutions were found for certain points that were (much) more expensive than the solutions with less passengers spilled. This can be seen for 25-09, 27-09, 02-10, 03-10 and 07-10. By definition, these points do reflect a point with Pareto optimality. However, these differences are explained by fleet availability. For example, the differences between the initial front and the rerun for 03-10-2019 are shown in Table 3. For the point with one passenger spilled cost savings are realized compared to the initial front. By spilling one passenger in Juba South, the Cessna is used less in that region, therefore making it available in the Juba East region to use instead of a more expensive aircraft. When three passengers are spilled in the Juba South region, the Cessna is actually used more in this region. It is therefore not available in the Juba North region anymore, forcing a more expensive aircraft to be used in the Juba North region.

These limitations are inherent in the method used to create the Pareto front. they show a weakness of the region division heuristic: reducing the cost in one region may increase the cost in another region, creating a counterproductive result in general. In practice, when a flight plan is selected with passengers spilled, a rerun should be conducted to check feasibility and savings possibilities. Because the solutions found during the initial computations can be used as a starting point, these reruns are relatively inexpensive regarding computational time.

Table 3 Elaborate overview of the cost difference between the separate reruns and the initial front for 03-10-2019 per region. The regions are depicted in solving order from left to right. See also Appx. H, Figure 46.

Pax spilled

Total	Rumbek region	Wau region	Juba West region	Juba South region	Juba North region	Juba North 2 region	Juba East region
0	0	0	0	0	0	0	0
1	0	0	0	1	0	0	0
2	0	0	0	2	0	0	0
3	0	0	0	3	0	0	0
4	0	0	0	0	0	4	0
5	0	0	0	1	0	4	0

Cost difference

Total	Rumbek region	Wau region	Juba West region	Juba South region	Juba North region	Juba North 2 region	Juba East region
0.0%	0%	0%	0%	0%	0%	0%	0%
-1.7%	0%	0%	0%	0%	0%	0%	-52%
0.0%	0%	0%	0%	0%	0%	0%	0%
2.8%	0%	0%	0%	0%	12%	3%	-52%
-0.2%	0%	0%	0%	0%	0%	0%	-4%
-1.9%	0%	0%	0%	0%	0%	0%	-52%

B. Validation

1. Expert Validation

Expert input was used to validate the routes generated by the model. This consisted of two parts: checking the routes generated by the model to validate the feasibility of these routes, and comparing the routes made by the model to routes created by an expert flight planner.

An expert flight planner with multiple years of experience working for UNHAS checked all the routes with 100% demand satisfaction, since these are the most challenging to program. It was found that all the produced routes were feasible routes.

To compare the performance of the model to human planning, the expert flight planner created routes for each day. This took him about 4 hours per day of data. Appendix E compares the flight plans from the human flight planner to those of the model, both for daily and monthly optimization.

Over the complete 2019 data set, the model (set to daily optimization) performed 3.5% better compared to the human flight planner when considering the block hour cost, as is shown in Table 4. However, this comparison is not fully valid, since the human flight planner did consider the 60 minimum guaranteed hours. When looking at the contract cost, the model (set to monthly optimization) outperformed the human flight planner by 0.6%. It can be seen that the contract structure has a dampening effect on the cost savings. This may also be because the minimum amount of flight hours seems to be quite high. Section VII.C.1 further elaborates on the effect of the amount of minimum guaranteed hours on the results of the model.

Table 4 Comparison of the total cost (2019 data set) between the current model (daily and monthly optimization, 100% demand satisfaction) and the human flight planner (considered mgh, 100% demand satisfaction).

	Block hour cost [-]	**Contract cost [-]** *mgh=60*
Current model	814,057	1,252,581
Human flight planner	843,773	1,260,548
	-3.5%	-0.6%

The following main differences were found between the flight plans of the flight planner and the model:

- **Region division**: the flight planner does not work with a region division like the model does. Therefore the flight planner was able to combine airports of different regions in one route.
- **Dash Q usage:** the flight planner sometimes chose not to use the Dash Q, compared to the model where it is forced to be used in the Juba West region.
- **Bor passengers:** in the model, Bor was added as a refueling stop for the Juba North region. However, passengers traveling from or to Bor can only be transported in the Juba East region. In contrast, the flight planner tries to first fill up all the flights that refuel at Bor with passengers, before a separate flight is planned. In some cases, this caused the model to plan an extra flight to Bor compared to the human flight planner.

Based on the comparison of the planned routes, the following adaptations to the region division heuristic were suggested by the flight planner:

- Yida and Ajung Thok should always be in the same region, due to their proximity.
- Akobo may be moved to the Juba East region
- Aburoc may be moved to the Rumbek region
- Malakal should be added to the Rumbek region as a refueling station
- Kuajok should be in the Wau region if the request size is 12 or lower (instead of 10 or lower).

Section VII.C.4 implements these adaptations and compares the results for both daily and monthly optimization.

2. Comparison to HFOM

To validate the model and its performance it was compared to the Humanitarian Flight Optimization Model (HFOM) as proposed by [19]. This model was tested on one week (5 days) of UNHAS data from 2015 and compared to the results of two human flight planners. The HFOM was able to find a feasible solution of good quality in approximately one hour.

Using the current model, Pareto fronts for the 2015 set were created, which were compared to the results of the reference model and the two human flight planners. In order to guarantee like-for-like comparison, the routes were created without considering the minimum guaranteed hours. The Pareto fronts can be found in Appendix F. To compare full Pareto fronts to single routes, two benchmark scenarios were constructed. Benchmark A keeps the amount of spilled passengers constant and evaluates the cost difference, whereas benchmark B tries to keep the cost constant and examines the difference in the amount of spilled passengers. Table 5 provides a comparison of the current model with two human flight planners and the reference model. For each benchmark, routes were selected from the Pareto fronts to compare to planner 1 (benchmark 1), planner 2 (benchmark 2) or the reference model (benchmark 3).

Table 5 Comparison between the reference model [19], human flight planners and benchmark points of the current model. Comparison based on full week of 2015 data.

	Pax transported	**Costs [-]**	**Δ pax**	**Δ objective**
Planner 1	1,676 (99.3%)	463,668	-	-
Planner 2	1,666 (98.8%)	434,139	-	-
Reference model (HFOM)	1,668 (98.9%)	424,598	-	-
Benchmark A 1	1,676 (99.3%)	426,202	0	-8.1% (wrt planner 1)
Benchmark A 2	1,666 (98.8%)	413,953	0	-4.6% (wrt planner 2)
Benchmark A 3	1,668 (98.9%)	416,758	0	-1.8% (wrt reference model)
Benchmark B 1	1,687 (100%)	442,032	+11	-4.7% (wrt planner 1)
Benchmark B 2	1,684 (99.8%)	432,776	+18	-0.3% (wrt planner 2)
Benchmark B 3	1,679 (99.5%)	424,785	+11	0.0% (wrt reference model)

With respect to the human flight planners, it can be seen that the current model provides solutions where the same amount of passengers can be transported with a cost reduction of 4.6 till 8.1%. For the same cost, the demand satisfaction can be improved by around 1%. When compared to the reference model, the model based on the novel formulation presented in this paper was able to realize a 1.8% cost reduction, or transport 11 more passengers.

However, the largest improvements are not in the cost improvement, but in the improved decision support. The novel formulation as presented in this paper allows for the spillage of part of a request, while the reference model relies on a heuristic where larger requests are split beforehand. This allows the current model to automatically create a Pareto Front, as described in Section V.G. Because for each day the full Pareto front can be created, a decision maker is able to select a point that best suits their needs. Table 6 provides an overview of the differences between the two models.

Table 6 Overview of key differences between the current model and the reference model from [19].

Current model	**Reference model (HFOM)**
Creates full Pareto Front	Creates single daily flight plan
Considers minimum guaranteed hours	Optimizes per day
15 minute take-off difference	No take-off difference
Allows spillage of single passenger	Can only spill full requests
Incorporates refueling	No refueling incorporated
3.5 till 9.5 hours computational time (full Pareto front)	1 hour computational time (single flight plan)
2% cheaper or 58% reduction in pax spilled compared to HFOM	Vice versa

C. Sensitivity Analysis

To evaluate the model's performance under varying input, a sensitivity analysis was performed. The focus of this sensitivity analysis lies on the monthly optimization, since this can be considered the most novel aspect of this research within the field of humanitarian flight optimization. An analysis of the amount of monthly guaranteed hours can be found in Section VII.C.1, and the pricing scheme is discussed in Section VII.C.2. The computational times are discussed in Section VII.C.3. Lastly, the adaptations to the model suggested by the expert flight planner are implemented and discussed in Section VII.C.4.

1. Minimum guaranteed hours

For UNHAS, the amount of monthly guaranteed flight hours equals 60. However, as can be seen in Figure 5, most aircraft do not reach this amount of flight hours. It is therefore interesting to analyze the behavior of the model for different amounts of minimum guaranteed hours. Two case studies were performed with 50 and 42 minimum guaranteed hours. The cumulated flight hours per aircraft can be found in Appx I, Figures 50 and 51.

Table 7 Overview of the costs, depending on the optimization method and minimum guaranteed hours considered. All solutions have a demand satisfaction of 100%.

	Block hour cost [-]	Contract cost [-] *mgh=42*	Contract cost [-] *mgh=50*	Contract cost [-] *mgh=60*
Daily optimization	814,057	1,077,780	1,165,909	1,302,078
Monthly opt. for mgh=42	859,595	973,915	-	-
Monthly opt. for mgh=50	876,796	-	1,091,58	-
Monthly opt. for mgh=60	885,979	-	-	1,252,581
		-9.6%	-6.4%	-4,0%

Table 7 provides an overview of the costs of the different optimization methods, depending on the contract structure. The four rows correspond to the four optimization methods tested: daily optimization or monthly optimization with 42, 50 or 60 guaranteed flight hours. The columns show the costs, considering different amounts of minimum guaranteed hours. Looking at the first column, it can be seen that the costs (without considering the mgh) increase as the mgh for which is optimized increases. However, when considering the minimum guaranteed hours, it can be seen that the optimization methods aimed at 42, 50 or 60 flight hours outperform the daily optimization by 9.6%, 6.4% and 4.0%, respectively.

Based on this analysis, it may be beneficial for UNHAS to renew the contracts with a lower amount of minimum guaranteed hours. Economically speaking it may be expected that a lease company will charge a higher hourly rate if the amount of guaranteed hours is lowered. Table 8 shows the cheapest solutions found for four contract options and the difference to the current contract. For example, at constant prices, a contract with a 42 minimum guaranteed hours will offer 22% savings. This means that renewing the contract to 42 guaranteed flight hours will be beneficial, if the average price increase is less than 22%.

Table 8 Cost differences between the cheapest solutions for differing mgh (with 100% demand satisfaction) and the cheapest solution for the current contract situation (mgh=60).

	Cheapest solution [-]	Price difference to current contract
mgh=60	1,252,581	0%
mgh=50	1,091,581	-12.9%
mgh=42	973,915	-22.2%
No mgh	814,057	-35.0%

2. Pricing scheme

For the cost calculations throughout this paper it has been assumed that the overtime costs are equal to the costs of the flight hours up to the minimum guaranteed hours. In reality this may differ. It is possible that overtime is cheaper or more expensive than the initial fees. However, as long as this pricing factor is the same for all aircraft this does not influence the model. All flight hours up to the minimum guaranteed hours can be considered sunken cost, reducing the objective to minimizing the amount of overtime. Since the model is linear, any linear change in cost does not influence the results, as long as the change is the same for all aircraft.

The challenge lies in selecting a pricing scheme for the model that properly reflects these considerations. Therefore, next to the pricing scheme shown in Figure 2, two other pricing schemes were tested. Figure 7 and 8 show these pricing schemes. For the test case the situation with 42 minimum guaranteed hours was selected, because this is the case where the difference between daily optimization and monthly optimization is the largest. Table 9 shows the results from the different pricing schemes for the 2019 data. The cumulated flight hours per day are depicted in Appendix I, Figures 52 and 53. It can be seen that, for this case, the original scheme performs the best. Alternative scheme 1 seems to be too lenient in penalizing overtime, resulting in a more expensive solution. Scheme 2, on the other hand, seems to be too strict. It does not allow for intermediate exceeding of the budget, resulting in a more expensive solution overall.

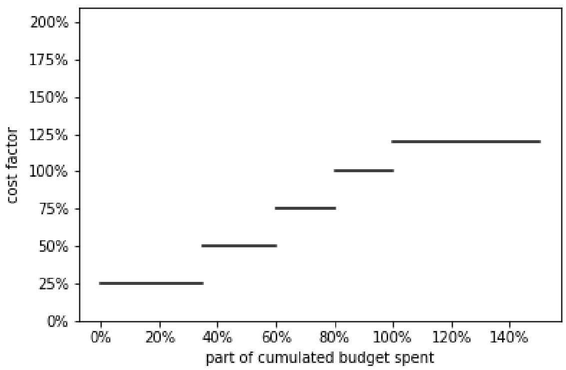

Fig. 7 Alternative dynamic pricing scheme 1.

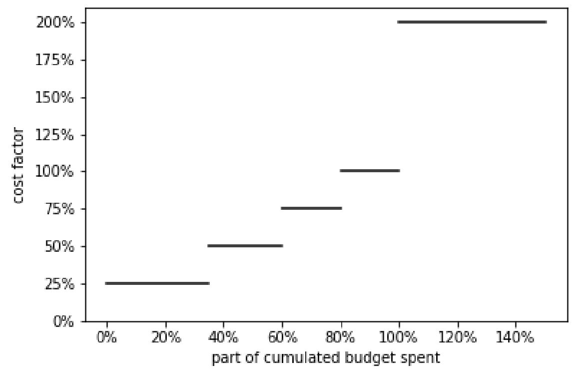

Fig. 8 Alternative dynamic pricing scheme 2.

Table 9 Difference in contract cost (for 11 days of 2019 data) between the different pricing schemes. Optimized for mgh=42, demand satisfaction=100%.

	Contract cost [-] *mgh=42*	**Difference to original scheme**
Original scheme (Figure 2)	973,915	0%
Alternative scheme 1 (Figure 7)	982,403	+0.9%
Alternative scheme 2 (Figure 8)	989,277	+1.6%

3. Computational time

To ensure the practical applicability of the model, it should be able to create a Pareto front within one night. For the academic purposes, slightly longer time limits were selected and relative large Pareto fronts were created. In practice, probably a solution with high demand satisfaction will be selected. Shorter computational times may be realized by creating smaller Pareto fronts, lowering the time limit or using more powerful hardware.

Figure 9 shows the computational times for the different days (monthly optimization with mgh=60) versus the amount of requests from that day. It is evident that a larger amount of requests leads to longer computational times.

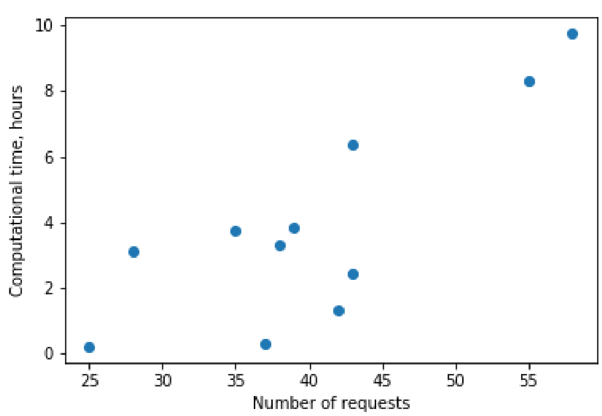

Fig. 9 Computational times versus the amount of requests per day. Computational times correspond to monthly optimization with mgh=60.

Table 10 Comparison between hardware used and modern reference hardware

	Hardware used *	**Reference laptop** †
Year	2013	2020
RAM	8.0 GB	16.0 GB
CPU	Intel Core i7-3630QM	Intel Core i7-9750H
Clock rate	2.4 GHz	4.5 GHz
Performance difference	0%	+87.5%

Lastly, it should be noted that all results in this model have been produced on a 7 year old laptop. It can be expected that performances improves when running the model on more modern hardware. Computational times are hard to predict and compare [16], however, Table 10 makes an attempt at providing a rough estimate of how the performance of the model may improve when run on more modern equipment. It can be seen that modern hardware could perform around 87.5% faster. Performance may be further improved by, for example, renting fast server space. When considering the cost improvements in the UNHAS case, the cost of investing in a fast computer (or renting server capacity) are easily earned back.

4. Region division

Based on the adaptations to the region division heuristic as proposed by the expert flight planner (see Section VII.B.1) the model was ran again. It is interesting to analyze how (small) adaptations to the region division impact the results. The adapted model was executed to create a flight plan with 0 passengers spilled for both daily and monthly optimization.

For the daily optimization mode, the results can be found in Table 11. Although for some individual days the adapted model found more expensive routes, it can be seen that for the total data set the adapted model performs 7.2% better than the original model, when regarding the block hour cost. Table 12 shows the results from running the adapted model for monthly optimization. It can be seen that the adapted model, when considering the minimum guaranteed hours, provides a solution that is 0.9 % less expensive than the original model. It should be noted that for the adapted model all aircraft are utilized less than the minimum guaranteed amount, meaning this solutions represents the cheapest solution possible. The cumulated flight hours for this solution can be found in Appx. I, Figure 54.

*HP EliteBook 8570w

†HP ZBook Studio G5 mobile Workstation

Table 11 Overview of the results per day from the initial model and the adapted model. For the adapted model the region division was altered based on input from the expert flight planner.

Day	Requests	Pax	*Initial model* Block hour cost [-] *0 pax spilled*	*Adapted model* Block hour cost [-] *0 pax spilled*
24-09	55	298	81,253	78,131
25-09	35	370	70,694	64,863
26-09	43	281	68,964	72,550
27-09	58	561	98,234	106,849
30-09	25	302	55,085	46,684
01-10	42	259	61,077	53,077
02-10	43	451	95,531	81,922
03-10	38	254	69,466	64,228
04-10	28	379	91,766	63,800
07-10	39	454	72,495	73,338
08-10	37	239	50,075	50,078
Total	443	3,848	814,057	755,520

Table 12 Comparison of the total cost (2019 data set) between the current model (monthly optimization, 100% demand satisfaction) and the adapted model (monthly optimization, 100% demand satisfaction).

	Block hour cost [-]	Contract cost [-] *mgh=60*
Adapted model	847,916	1,240,800
Current model	885,979	1,252,581
	-4.3%	-0.9%

Table 13 compares the results from the adapted model to those of the human flight planner. The adapted model performs 10.5% (daily optimization) or 1.6% (monthly optimization) better than the human flight planner. It should be noted again that the flight planner did consider the minimum guaranteed hours while planning, making the comparison to the daily optimization mode of the model not fully relevant.

It is evident that the relative small adaptations suggested by the flight planner significantly improve the results. This underlines the weakness of the region division heuristic: small changes can have a large effect on the solution. In practice, the model should be used interactively with expert planners to continuously tweak these settings.

Table 13 Comparison of the total cost (2019 data set) between the adapted model (daily and monthly optimization, 100% demand satisfaction) and the human flight planner (considered mgh, 100% demand satisfaction).

	Block hour cost [-]	Contract cost [-] *mgh=60*
Adapted model	755,520	1,240,800
Human flight planner	843,773	1,260,548
	-10.5%	-1.6%

VIII. Conclusion

This sections reflects on the results produced by the model. Section VIII.A discusses the conclusions from an academic perspective, Section VIII.B focuses on the application possibilities for UNHAS and Section VIII.C provides recommendations for further research.

A. Research

Addressing the research objective and questions presented in Section II, it can be concluded that a linear programming model has been created that improved the efficiency and effectiveness of flight routing and scheduling in a humanitarian setting taking into account the operational and safety constraints specific to non-commercial humanitarian air transport. The novel formulation has greatly reduced the number of required nodes and therefore simplified the formulation. Using a dynamic pricing method, monthly optimization was realized (without using rolling horizon planning) that offered cost savings of 4.0%, compared to executing the model in the daily optimization mode. The model is capable of creating a Pareto front for each day within reasonable time, although it was found that not all points correspond to feasible solutions. Also the region division heuristic, although effective in reducing the problem size, proved limiting in finding a fully optimal solution. It can be concluded that both the novel formulation of the linear problem and the dynamic pricing monthly optimization method showed promising results and are of interest for further academic research.

B. Application to UNHAS

A new model was created, specifically tailored to humanitarian operations. The following aspects were realized:

- Feasible route creation that considers all operational constraints, including the required 15 minute take-off difference between aircraft.
- Cost savings of 4.6% till 10.5% compared to human flight planners, when considering the block hour costs.
- Improved demand satisfaction of up to 1.2%.
- Possibility to optimize considering the monthly minimum guaranteed flight hours, offering a cost reduction of 1.6% compared to the human flight planner and 4% compared to the model set to daily optimization mode.
- Elaborate decision support from the Pareto front that can be created within an acceptable time limit.
- Insight in the effect of the wet lease contract structure on the monthly costs, offering savings up to 35% at constant prices.

C. Recommendations

The model based on the novel formulation of the vehicle routing problem for humanitarian applications has shown promising results regarding cost savings, demand satisfaction improvement, monthly optimization, daily flight optimization, contract efficiency insight and decision support. However, more research is needed to further improve flight optimization in humanitarian settings. The following research areas can be of interest:

- **Fleet planning:** the fleet has been considered as a given input in this research. Research on an optimal fleet composition can be beneficial. Additionally, analysis of optimal base locations for the different aircraft may offer cost savings in the short run for UNHAS, without having to change the fleet composition.
- **Dynamic region division heuristic:** this research made a small first step in having a dynamic region division. A fully dynamic region division heuristic, based on the requests of that day, can further improve the cost efficiency and general applicability of the model. Clustering algorithm available in literature may be of interest.
- **Computational time:** limitations of this research included the limited computational power of the test set up. Behavior of the model should be tested on faster computers or servers. Perhaps it may also be possible to reduce the number of regions due to higher computing power.
- **Uncertainty:** this research took a deterministic approach to the flight schedule. In real life, delays exists due to many reasons. Research can be done on incorporating this in the model.
- **Weekly schedule:** UNHAS has a weekly schedule which dictates which airports are flown to on which day. Research on optimization of this schedule could be performed.
- **Field testing:** the model should be tested on larger data sets, or even in a practical field setting to really research the practical value. It would be interesting the run the model for a longer amount of time parallel to a human flight planner to further analyze the behavior of the model.
- **Contracting:** analysis based on different scenarios regarding block hour cost, minimum guaranteed hours and overtime cost can offer further valuable insight in the effect of the contract structure on UNHAS operational cost.

Appendices

A. Region Division

Figure 1 shows the different locations and their respective regions. The hub airports are not only part of the Juba West region, as shown in the figure, but are also part of the regions named after them. Refueling is possible in Juba, Rumbek, Wau, Bor and Malakal. The fuel prices in Malakal are much higher than the other locations. Table 15 shows the airports that are part of the set N^{-k} for helicopters based in Rumbek or Juba.

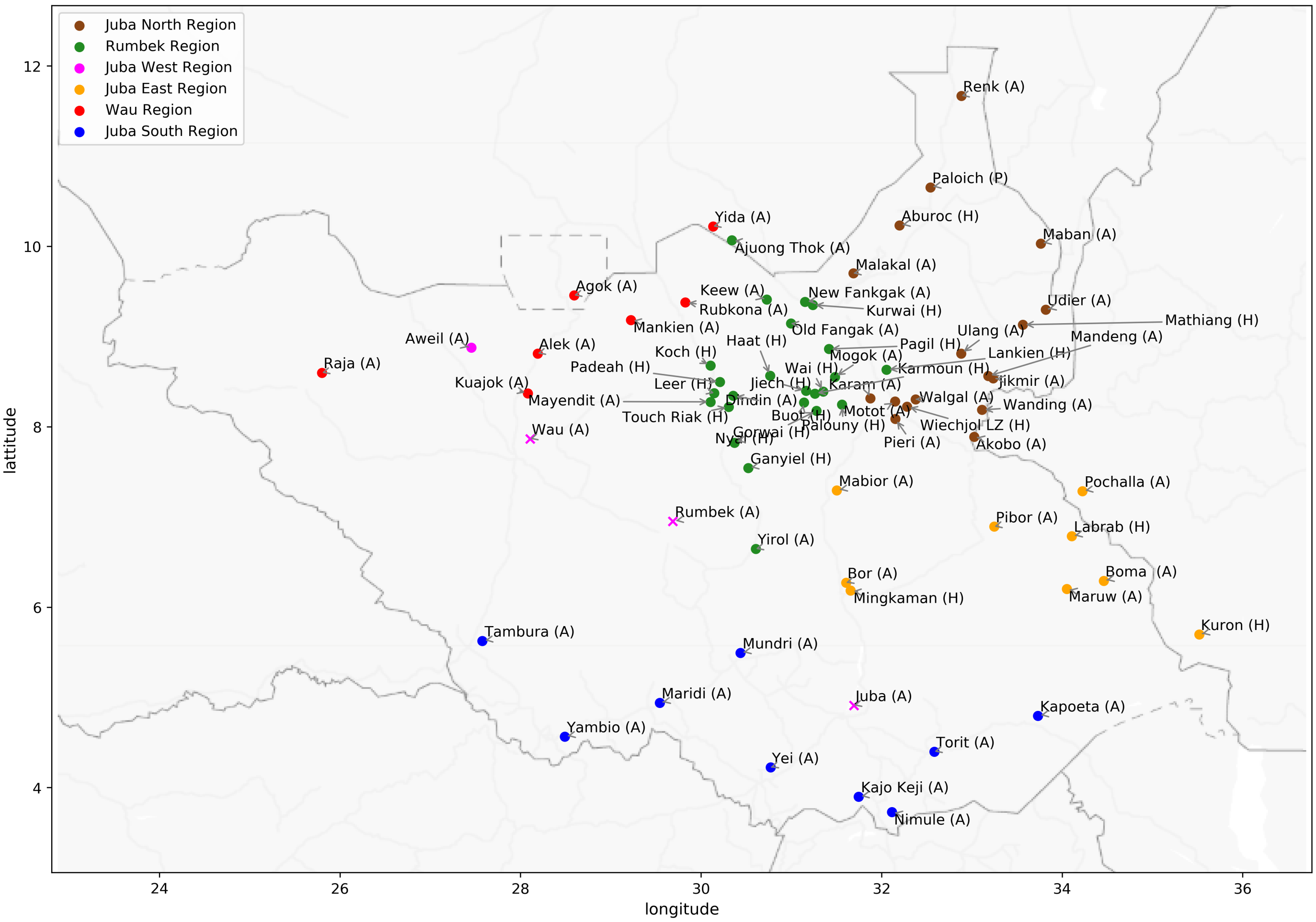

Fig. 10 Division of the airports in regions. Base airports for one or multiple aircraft are indicated with a cross.

To improve the solution quality, some dynamic elements were incorporated in the region division heuristic. For passengers traveling from Juba to the Rumbek or Wau region (or vice versa) it is generally more efficient to schedule a transit in Rumbek or Wau. This is because the flights from Juba to Rumbek and Wau are scheduled already anyway. However, if such a request consists of more than 12 passengers (the capacity of a Cessna, the only airplane based in Rumbek or Wau) passengers will definitely be spilled. In this case it is better to not schedule a transit, but move the entire request to a different region and fly directly from Juba with a larger aircraft. To incorporate this in the region division heuristic, five airports are assigned to different regions depending on the amount of requested passengers. Table 14 gives an overview of the concerning airports. In some cases, the Juba North region became too large to solve. Therefore a second dynamic aspect was added. If the total amount of airports in the Juba North region exceeds 12, part of the region is transferred to a new region: the Juba North 2 region. In this case the Juba North 2 region consists of the airports named in 14 (in the case they are not part of the Rumbek or Wau region) and Aburoc, Malakal, Paloich and Renk.

Table 14 Dynamic region assignment based on amount of passengers per airport.

Airport	Region if #pax ≤ 10	Region if #pax > 10
Ajuong Thok	Rumbek	Juba North
Kuajok	Wau	Juba North
Mankien	Wau	Juba North
Rubkona	Wau	Juba North
Mankien	Wau	Juba North

Table 15 Airports that are not removed as possible destination for helicopters, based on the base of the helicopter.

Rumbek				Juba	
RUM	BUOT	PAGL	MENIM	JUB	BOR
GANY	PALON	WAI	MAYEN	MINGK	DOR
JCH	TOUCH	HAAT	LKEN	LABR	POCAL
KOCH	PADEA	MOGOK	NEWFG	ABURO	PIBR
KUACH	KARMO	YIROL	OLDFG	MATHI	BOMA
KURWA	DINDI	GORWA		WCHJL	MARUW
LER	KEEW	NYAL			

B. Input Data

The 2019 data set consists of fleet data (Table 16), airport data (Table 17), and request data (Table 18 and 19). All the costs mentioned are unitless since this is sensitive information. However, the ratio between the cost reflect the real life problem.

Table 16 Overview of the fleet data. The required runway length is a virtual length to distinguish between the different categories.

Name	Type	Speed [kts]	Cost [-/nm]	Base	Seats	Range [nm]	Runway required
Dash8Q	Q-400	300	22.89	Juba	71	1100	3000
Dash8_1	DHC-3	287	11.54	Juba	49	924	2000
Dash8_2	DHC-2	289	9.51	Juba	37	1125	2000
Dornier_1	D-228	170	13.96	Juba	18	600	1000
Dornier_2	D-228	170	13.96	Juba	18	600	1000
Let_1	L-410	170	13.35	Juba	17	415	1000
Let_2	L-410	170	14.75	Juba	17	415	1000
Cessna	C-208B	186	6.73	Juba	12	1070	1000
Mi8_1	MI-8 T	120	23.85	Juba	19	355	50
Mi8_2	MI-8 MTV	120	28.86	Juba	19	355	50
Mi8_1R	MI-8 T	120	23.85	Rumbek	19	355	50
Mi8_2R	MI-8 T	120	19.58	Rumbek	19	355	50
Cessna_1R	C-208B	186	6.73	Rumbek	12	1070	1000
Cessna_1W	C-208B	186	5.97	Wau	12	1070	1000

Table 17 Overview of all the airport data. The runway length is a virtual length to distinguish between the different categories.

Code	Name	Lat	Long	Runway	Code	Name	Lat	Long	Runway
ABURO	Aburoc (H)	10.23	32.20	50	MANK	Mankien (A)	9.19	29.22	1000
AGOK	Agok (A)	9.46	28.59	1000	MARID	Maridi (A)	4.94	29.54	1000
AJUON	Ajuong Thok (A)	10.07	30.34	1000	MARUW	Maruw (A)	6.20	34.05	1000
ALEK	Alek (A)	8.81	28.19	1000	MATHI	Mathiang (H)	9.13	33.56	50
AWL	Aweil (A)	8.88	27.45	3000	MAYEN	Mayendit (A)	8.28	30.10	1000
BOMA	Boma (A)	6.29	34.46	1000	MENIM	Menime (H)	8.67	30.73	50
BOR	Bor (A)	6.27	31.61	1000	MINGK	Mingkaman (H)	6.19	31.66	50
BUOT	Buot (H)	8.27	31.14	50	MOGOK	Mogok (A)	8.55	31.48	1000
DINDI	Dindin (A)	8.34	30.36	1000	MOTO	Motot (A)	8.28	32.15	1000
DRN	Dorein (A)	6.62	33.29	1000	MUNDR	Mundri (A)	5.49	30.44	1000
GANY	Ganyiel (H)	7.54	30.52	50	NEWFG	New Fankgak (A)	9.39	31.15	1000
GORWA	Gorwai (H)	8.18	31.28	50	NIMU	Nimule (A)	3.73	32.11	1000
GUM	Gum (A)	8.81	33.12	1000	NYAL	Nyal (H)	7.83	30.37	50
HAAT	Haat (H)	8.57	30.76	50	OLDFG	Old Fangak (A)	9.15	30.99	1000
HSAK	Akobo (A)	7.89	33.03	1000	PADEA	Padeah (H)	8.50	30.21	50
HSPA	Paloich (A)	10.66	32.54	2000	PAGL	Pagil (H)	8.86	31.41	50
HSRN	Renk (A)	11.67	32.88	1000	PALON	Palouny (H)	8.25	31.56	50
HSTR	Torit (A)	4.40	32.58	1000	PGK	Pagak (A)	8.54	34.13	1000
JCH	Jiech (H)	8.40	31.16	50	PIBR	Pibor (A)	6.89	33.25	1000
JIKMI	Jikmir (A)	8.54	33.23	1000	PIERI	Pieri (A)	8.09	32.15	1000
JUB	Juba (A)	4.91	31.69	3000	POCAL	Pochalla (A)	7.29	34.22	1000
KAPO	Kapoeta (A)	4.80	33.73	1000	RAJA	Raja (A)	8.60	25.80	1000
KARAM	Karam (A)	8.32	31.88	1000	RUB	Rubkona (A)	9.38	29.83	2000
KARMO	Karmoun (H)	8.37	31.26	50	RUM	Rumbek (A)	6.95	29.69	3000
KEEW	Keew (A)	9.41	30.73	1000	TAMBU	Tambura (A)	5.63	27.58	1000
KJK	Kajo Keji (A)	3.90	31.74	1000	TOUCH	Touch Riak (H)	8.22	30.31	50
KOCH	Koch (H)	8.68	30.10	50	UDR	Udier (A)	9.30	33.82	1000
KUACH	Kuach (H)	8.91	30.13	50	ULANG	Ulang (A)	8.81	32.88	1000
KUAJK	Kuajok (A)	8.37	28.08	1000	WAI	Wai (H)	8.39	31.35	50
KURN	Kuron (H)	5.70	35.52	1000	WAT	Waat (A)	8.32	32.15	1000
KURWA	Kurwai (H)	9.35	31.24	50	WAU	Wau (A)	7.87	28.11	3000
LABR	Labrab (H)	6.79	34.11	50	WCHJL	Wiechjol LZ (H)	8.23	32.28	50
LER	Leer (H)	8.38	30.14	50	WDG	Wanding (A)	8.19	33.11	1000
LKEN	Lankien (A)	8.63	32.05	50	WGK	Walgal (A)	8.31	32.38	1000
MABAN	Maban (A)	10.03	33.76	2000	YAM	Yambio (A)	4.57	28.49	2000
MABR	Mabior (A)	7.30	31.50	1000	YEI	Yei (A)	4.23	30.77	2000
MAK	Malakal (A)	9.70	31.69	3000	YIDA	Yida (A)	10.22	30.13	1000
MANDE	Mandeng (A)	8.56	33.18	1000	YIROL	Yirol (A)	6.65	30.61	1000

Table 18 Request data for 24 till 30 September 2019

24/Sep		
From	To	Count
ABURO	JUB	4
ABURO	MAK	1
ALEK	JUB	1
AWL	JUB	8
BOMA	JUB	4
BOR	JCH	2
BOR	MABR	2
BOR	PIBR	1
GANY	JUB	3
GORWA	JUB	1
HSPA	JUB	4
HSRN	JUB	4
HSTR	JUB	6
JCH	BOR	2
HSTR	KAPO	2
JCH	JUB	9
JUB	ABURO	2
JUB	AGOK	8
JUB	AJUON	1
JUB	ALEK	2
JUB	AWL	18
JUB	BOMA	4
JUB	BOR	6
JUB	BUOT	1
JUB	GANY	4
JUB	HSPA	5
JUB	HSRN	11
JUB	HSTR	11
JUB	JCH	8
JUB	KAPO	2
JUB	KUAJK	7
JUB	MABR	7
JUB	MARID	2
JUB	NYAL	4
JUB	PAGL	1
JUB	PIBR	9
JUB	POCAL	2
JUB	RUM	10
JUB	WAU	13
JUB	WGK	18
JUB	YEI	17
KAPO	JUB	1
KUAJK	JUB	1
MABR	JUB	2
MARID	JUB	7
MUNDR	JUB	2
NYAL	JUB	1
PAGL	JUB	1
PIBR	BOR	1
PIBR	JUB	6
POCAL	JUB	2
RUM	JUB	8
WAI	JUB	1
WAU	JUB	27
YEI	JUB	11

25/Sep		
From	To	Count
AJUON	JUB	17
BOR	JUB	2
HSTR	JUB	7
JUB	AJUON	16
JUB	BOR	18
JUB	HSTR	2
JUB	KURN	8
JUB	MABAN	36
JUB	MAK	27
JUB	NEWFG	6
JUB	OLDFG	8
JUB	RUB	21
JUB	RUM	8
JUB	TAMBU	9
JUB	ULANG	5
JUB	WAU	24
JUB	YAM	12
JUB	YEI	1
JUB	YIDA	6
KURN	JUB	8
KURWA	JUB	1
MABAN	JUB	15
MAK	JUB	14
MINGK	JUB	2
NEWFG	JUB	2
OLDFG	JUB	4
RAJA	WAU	2
RUB	JUB	15
RUM	JUB	15
TAMBU	JUB	11
ULANG	JUB	13
WAU	JUB	11
WAU	RAJA	1
YAM	JUB	16
YIDA	JUB	7

26/Sep		
From	To	Count
AGOK	JUB	7
AWL	JUB	9
BOR	JUB	8
HSAK	JUB	5
HSPA	JUB	7
HSRN	JUB	2
HSTR	JUB	17
JIKMI	JUB	9
JUB	AGOK	10
JUB	ALEK	4
JUB	AWL	9
JUB	BOR	6
JUB	BUOT	1
JUB	HSAK	8
JUB	HSPA	4
JUB	HSRN	3
JUB	HSTR	3
JUB	JIKMI	7
JUB	KAPO	7
JUB	KJK	6
JUB	KOCH	5
JUB	KUAJK	10
JUB	MANK	5
JUB	MATHI	2
JUB	NIMU	11
JUB	POCAL	2
JUB	RUM	4
JUB	WAU	18
JUB	YEI	4
JUB	YIROL	9
KAPO	JUB	4
KJK	JUB	1
KOCH	JUB	7
KUAJK	JUB	7
MANK	JUB	2
MATHI	JUB	5
POCAL	JUB	1
RUM	JUB	13
WAI	BOR	1
WAU	AWL	2
WAU	JUB	17
YEI	JUB	14
YIROL	JUB	5

27/Sep		
From	To	Count
AGOK	JUB	2
AJUON	JUB	15
AWL	JUB	20
AWL	WAU	2
BOR	JUB	23
GANY	JUB	9
GANY	NYAL	2
HSPA	HSRN	1
HSTR	JUB	1
JUB	AGOK	5
JUB	AJUON	15
JUB	AWL	8
JUB	BOR	16
JUB	GANY	5
JUB	HSTR	2
JUB	JCH	1
JUB	KAPO	2
JUB	KARAM	1
JUB	LER	3
JUB	LKEN	4
JUB	MABAN	13
JUB	MAK	30
JUB	MAYEN	6
JUB	MINGK	2
JUB	NYAL	6
JUB	PALON	7
JUB	PIBR	18
JUB	PIERI	1
JUB	RUB	25
JUB	RUM	16
JUB	TOUCH	7
JUB	ULANG	4
JUB	WAU	18
JUB	WCHJL	2
JUB	YAM	22
JUB	YEI	1
JUB	YIDA	9
KARAM	JUB	2
LER	JUB	4
LKEN	JUB	8
MABAN	JUB	19
MAK	JUB	27
MAYEN	JUB	1
MINGK	JUB	1
NYAL	JUB	3
PIBR	BOR	1
PIBR	JUB	14
RUB	JUB	21
RUM	JUB	16
TOUCH	JUB	2
ULANG	JUB	13
WAU	JUB	23
WCHJL	JUB	3
WDG	JUB	5
YAM	JUB	16
YEI	JUB	2
YIDA	JUB	5

30/Sep		
From	To	Count
AJUON	JUB	13
BOR	JUB	15
HSTR	JUB	7
JUB	AJUON	12
JUB	BOR	20
JUB	HSTR	12
JUB	KAPO	11
JUB	KEEW	3
JUB	LKEN	12
JUB	MAK	29
JUB	MINGK	8
JUB	PADEA	6
JUB	RUM	24
JUB	WAU	22
JUB	YAM	29
JUB	YIDA	4
KAPO	JUB	6
LER	DINDI	9
LKEN	JUB	4
MAK	JUB	13
MINGK	JUB	2
RUM	JUB	8
WAU	JUB	17
YAM	JUB	15
YIDA	JUB	1

Table 19 Request data for 1 till 8 October 2019

01/Oct

From	To	Count
AGOK	JUB	8
BOMA	JUB	3
BOR	MABR	2
BUOT	JUB	3
BUOT	KARMO	15
GANY	JUB	4
HSPA	JUB	1
HSRN	JUB	6
HSTR	JUB	3
JCH	JUB	1
JUB	AGOK	10
JUB	BOMA	1
JUB	GANY	5
JUB	HSPA	4
JUB	HSRN	6
JUB	HSTR	6
JUB	JCH	5
JUB	KUAJK	9
JUB	MABR	5
JUB	MARID	4
JUB	MOGOK	1
JUB	MUNDR	1
JUB	NYAL	2
JUB	PAGL	1
JUB	PIBR	14
JUB	POCAL	7
JUB	RUM	24
JUB	WAU	13
JUB	YEI	16
KUAJK	JUB	12
MABR	BOR	1
MABR	JUB	7
MARID	JUB	2
NYAL	JUB	4
PAGL	JUB	1
PIBR	BOR	8
PIBR	JUB	10
POCAL	BOR	1
POCAL	JUB	2
RUM	JUB	7
WAU	JUB	16
YEI	JUB	8

02/Oct

From	To	Count
AJUON	JUB	12
BOR	JUB	9
GORWA	HAAT	17
HSAK	JUB	11
HSRN	JUB	10
JUB	AJUON	11
JUB	BOR	15
JUB	HSAK	6
JUB	HSRN	10
JUB	KURWA	1
JUB	MABAN	63
JUB	MAK	17
JUB	MINGK	3
JUB	MOTO	3
JUB	NEWFG	8
JUB	NIMU	1
JUB	NYAL	4
JUB	OLDFG	10
JUB	RUB	46
JUB	RUM	4
JUB	TAMBU	3
JUB	ULANG	20
JUB	WAU	7
JUB	YAM	19
JUB	YEI	1
JUB	YIDA	3
MABAN	JUB	32
MAK	JUB	19
MINGK	BOR	1
MINGK	JUB	1
MOTO	JUB	3
NEWFG	JUB	10
NYAL	JUB	2
OLDFG	JUB	1
RUB	JUB	29
RUM	JUB	6
TAMBU	JUB	2
ULANG	JUB	10
WAU	JUB	7
YAM	JUB	9
YEI	JUB	1
YIDA	JUB	3

03/Oct

From	To	Count
AGOK	JUB	3
BOR	JUB	5
HSAK	JUB	4
HSPA	JUB	2
HSRN	JUB	9
HSTR	JUB	19
JIKMI	JUB	5
JUB	AGOK	10
JUB	BOR	3
JUB	DINDI	9
JUB	HSAK	4
JUB	HSPA	3
JUB	HSRN	4
JUB	HSTR	6
JUB	JIKMI	11
JUB	KJK	5
JUB	KOCH	8
JUB	KUAJK	3
JUB	MANK	7
JUB	MATHI	9
JUB	NIMU	5
JUB	RUM	7
JUB	WAU	6
JUB	WGK	18
JUB	YEI	5
JUB	YIROL	3
KJK	JUB	1
KOCH	JUB	6
KUAJK	JUB	11
MANK	JUB	7
MATHI	JUB	2
NIMU	JUB	3
RUM	JUB	15
WAU	JUB	13
YEI	JUB	15
YIROL	JUB	5

04/Oct

From	To	Count
AJUON	JUB	17
BOR	JUB	8
BOR	LABR	6
BOR	MARUW	6
JUB	AJUON	12
JUB	BOR	16
JUB	JUB	71
JUB	MABAN	28
JUB	MAK	13
JUB	MATHI	3
JUB	MINGK	1
JUB	PALON	10
JUB	PIBR	19
JUB	RUB	18
JUB	UDR	1
JUB	YAM	10
JUB	YIDA	7
MABAN	JUB	20
MAK	JUB	25
MANDE	JUB	8
MINGK	JUB	3
PIBR	JUB	12
RUB	JUB	28
WAU	JUB	9
WCHJL	JUB	3
YAM	JUB	12
YEI	JUB	4
YIDA	JUB	9

07/Oct

From	To	Count
AGOK	JUB	7
AJUON	JUB	5
AWL	JUB	19
BOR	JUB	13
HSAK	BOR	1
HSAK	JUB	8
JUB	AGOK	4
JUB	AJUON	6
JUB	AWL	22
JUB	BOR	23
JUB	HSAK	18
JUB	LKEN	14
JUB	MABAN	26
JUB	MAK	30
JUB	MOGOK	3
JUB	NEWFG	6
JUB	PIERI	2
JUB	RAJA	4
JUB	RUB	35
JUB	RUM	13
JUB	WAU	16
JUB	YAM	16
JUB	YIDA	4
KOCH	JUB	6
LKEN	JUB	4
MABAN	JUB	16
MAK	JUB	24
MANK	JUB	5
MINGK	JUB	2
PADEA	JUB	2
RAJA	WAU	9
RUB	JUB	12
RUM	JUB	14
WAU	JUB	19
WAU	RAJA	5
YAM	JUB	25
YIDA	JUB	10

08/Oct

From	To	Count
ALEK	JUB	2
AWL	JUB	18
AWL	WAU	1
BOMA	JUB	1
BOR	PIBR	4
BOR	POCAL	1
GANY	JUB	4
GORWA	JUB	3
JCH	JUB	3
JUB	ALEK	2
JUB	AWL	19
JUB	BOMA	8
JUB	BOR	1
JUB	GANY	4
JUB	JCH	4
JUB	KAPO	10
JUB	KUAJK	15
JUB	MARID	2
JUB	MUNDR	2
JUB	NYAL	4
JUB	PIBR	14
JUB	POCAL	5
JUB	RUM	10
JUB	WAU	12
JUB	YEI	18
KAPO	JUB	6
KUAJK	JUB	5
MARID	JUB	2
MOGOK	JUB	3
MUNDR	JUB	1
NYAL	JUB	7
PIBR	JUB	13
POCAL	JUB	2
RUM	JUB	4
WAU	JUB	11
YEI	JUB	18

C. Auxiliary Constraints

As described in Section V.C, several auxiliary constraints were added to the model. These constraints can be found in Eq. 26 till 43. Extending on the nomenclature provided in Section I: AC is the set of all aircraft types, and F^m is the set of all aircraft k that are of type m. Two penalty decision variables are introduced: π^k_{order} and π_Q, which are further explained in Section V.D and Appendix D.

$$w_{d_i}^{k} \leq w_{a_j}^{k} \qquad \forall k \in K,\ \forall n \in N^{-k},\ \forall i, j \in E_n \mid i < j \tag{26}$$

$$\sum_{(i,j)\in A^{k_1}} t_{ij}^{k_1} \cdot x_{ij}^{k_1} \geq \sum_{(i,j)\in A^{k_2}} t_{ij}^{k_2} \cdot x_{ij}^{k_2} - \pi^{k_1}_{order} \qquad \forall k \in K,\ \forall m \in AC,\ \forall k_1, k_2 \in F^m \mid k_1 < k_2 \tag{27}$$

$$\sum_{(i,j)\in A_k \mid d^k_{ij}>0} x_{ij}^{k} \geq 1 - \pi_Q \qquad \text{for } k \text{ is Dash\_Q} \tag{28}$$

$$\sum_{(i,j)\in A^k \mid d^k_{ij}>0} x_{ij}^{k} \leq 5 \qquad \forall k \in K \tag{29}$$

$$\sum_{i\in V^{+k}} y_{p_i}^{rk} \leq 1 \qquad \forall k \in K,\ \forall r \in R \tag{30}$$

$$\sum_{i\in V^{+k}} y_{d_i}^{rk} \leq 1 \qquad \forall k \in K,\ \forall r \in R \tag{31}$$

$$\sum_{k\in K}\sum_{i\in V^{+k}} y_{p_i}^{rk} \leq 6 \qquad \forall r \in R \tag{32}$$

$$\sum_{k\in K}\sum_{i\in V^{+k}} y_{d_i}^{rk} \leq 6 \qquad \forall r \in R \tag{33}$$

$$\sum_{i\in V^{+k}} q_{p_i}^{rk} \leq q^r_{req} \qquad \forall k \in K,\ \forall r \in R \tag{34}$$

$$\sum_{i\in V^{+k}} q_{d_i}^{rk} \leq q^r_{req} \qquad \forall k \in K,\ \forall r \in R \tag{35}$$

$$\sum_{j:(j,i)\in A^k} x_{ji}^{k} \leq 1 \qquad \forall k \in K,\ \forall i \in V^{+k} \tag{36}$$

$$\sum_{j:(i,j)\in A^k} x_{ij}^{k} \leq 1 \qquad \forall k \in K,\ \forall i \in V^{+k} \tag{37}$$

$$\sum_{k\in K}\sum_{i\in V^{+k}} y_{p_i}^{rk} = \sum_{k\in K}\sum_{i\in V^{+k}} y_{d_i}^{rk} \qquad \forall r \in R \tag{38}$$

$$\sum_{k\in K}\sum_{i\in V^{+k}} q_{p_i}^{rk} = \sum_{k\in K}\sum_{i\in V^{+k}} q_{d_i}^{rk} \qquad \forall r \in R \tag{39}$$

$$\sum_{r\in R}\sum_{i\in V^{+k}} y_{p_i}^{rk} = \sum_{k\in K}\sum_{i\in V^{+k}} y_{d_i}^{rk} \qquad \forall k \in K \tag{40}$$

$$\sum_{r\in R}\sum_{i\in V^{+k}} q_{p_i}^{rk} = \sum_{k\in K}\sum_{i\in V^{+k}} q_{d_i}^{rk} \qquad \forall k \in K \tag{41}$$

$$\sum_{r\in R}\sum_{k\in K}\sum_{i\in V^{+k}} y_{p_i}^{rk} = \sum_{k\in K}\sum_{i\in V^{+k}} y_{d_i}^{rk} \tag{42}$$

$$\sum_{r\in R}\sum_{k\in K}\sum_{i\in V^{+k}} q_{p_i}^{rk} = \sum_{k\in K}\sum_{i\in V^{+k}} q_{d_i}^{rk} \tag{43}$$

D. Normalization

As described in Section V.F, the different parts of the objective function are normalized (based on their maximum value) and assigned weights (based on their relative importance to the solution). Including all the penalties described in Section V.F, the functions described in Equation 25 are given by Equation 44 till 50.

$$f_0 = \sum_{k \in K} \sum_{(i,j) \in A^k} c_{ij}^k x_{ij}^k \tag{44}$$

$$f_1 = \sum_{r \in R} \left(q_{req}^r - \sum_{k \in K} \sum_{i \in V^{+k}} q_{p_i}^{rk} \right) \tag{45}$$

$$f_2 = \sum_{k \in K} \sum_{i \in N^{+k}} u_i^k \tag{46}$$

$$f_3 = \sum_{k \in K} \pi_{order}^k \tag{47}$$

$$f_4 = \sum_{k \in K} w_{a_i}^k \quad \text{if } i \text{ is end depot} \tag{48}$$

$$f_5 = \sum_{k \in K} \pi_{fuel}^k \tag{49}$$

$$f_6 = \sum_{k \in K} \pi_Q \tag{50}$$

The penalty variables π_{order}^k and π_Q are defined in Appendix C, Eq. 27 and 28, respectively. For the Malakal fuel penalty, π_{fuel}^k, Constraint 21 is replaced by Eq. 51.

$$\text{if } x_{ij}^k = 1: \quad v_j^k \geq v_i^k + d_{ij} - \pi_{fuel}^k \qquad \forall k \in K,\ \forall (i,j) \in A^k,\ \text{if } i \text{ is Malakal} \tag{51}$$

Eq. 52 till 58 give the estimated maximum and assigned weight for the different function parts. The weights were assigned based on estimated relevance of the function parts through an iterative process. For f_0, the cost function, the maximum function value is estimated as the average cost of a round trip from the hub to each node. However, in cases with a small number of nodes, this approximation approaches the minimum. Therefore a correction factor (the first term of Eq. 52) was added. The maximum for f_1, the spillage penalty, is the total number of passengers requested. For the passengers on first leg penalty, f_2, the maximum is the sum of the capacities of the fleet. For both f_3, the fleet order penalty, and f_4, the time penalty, the maximum is the maximum time (10 hours in this case) times the fleet size. For the fuel penalty in Malakal, it was estimated that refueling will take place at most 4 times. Therefore the maximum value of f_5 was set at 4 times the minimum range of the fleet. The maximum for f_6 equals 1.

$$f_{0max} = \frac{7}{|N|^{1.2}} \cdot \frac{2}{|K|} \cdot \sum_{k \in K} \sum_{j \in N^{-k}} c_{hub,j}^k \qquad \mu_0 = 0.45 \tag{52}$$

$$f_{1max} = \sum_{r \in R} q_{req}^r \qquad \mu_1 = 9 \tag{53}$$

$$f_{2max} = \sum_{k \in K} Q^k \qquad \mu_2 = 0.05 \tag{54}$$

$$f_{3max} = 10 \cdot |K| \qquad \mu_3 = 0.01 \tag{55}$$

$$f_{4max} = 10 \cdot |K| \qquad \mu_4 = 0.01 \tag{56}$$

$$f_{5max} = 4 \cdot \min\{ra^1, ra^2, \ldots ra^k\} \qquad \mu_5 = 0.01 \tag{57}$$

$$f_{6max} = 1 \qquad \mu_6 = 0.5 \tag{58}$$

E. Results 2019

A. Daily optimization

This section presents the results for the 2019 model when set for daily optimization. The results of the human flight planner are also presented. It should be noted that the flight planner did consider the minimum guaranteed hours when planning his routes. Figures 11 till 21 show the Pareto fronts for the 2019 data. These figures result from the daily optimization setting.

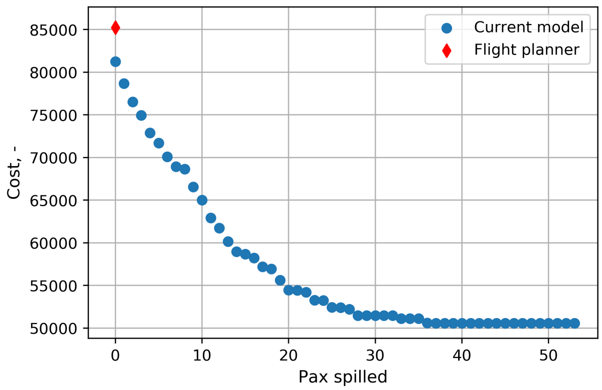

Fig. 11 Comparison of the results for 24-09-2019 made by the current model (daily optimization) and a human flight planner.

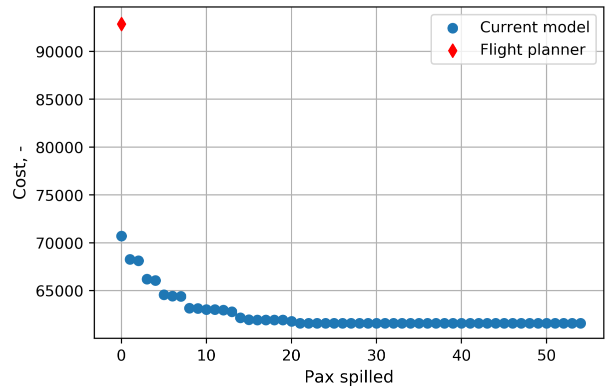

Fig. 12 Comparison of the results for 25-09-2019 made by the current model (daily optimization) and a human flight planner.

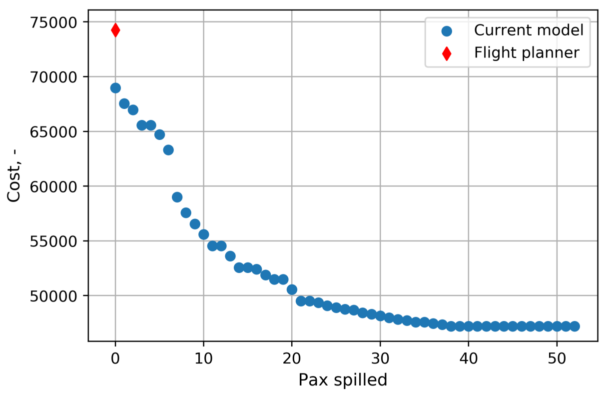

Fig. 13 Comparison of the results for 26-09-2019 made by the current model (daily optimization) and a human flight planner.

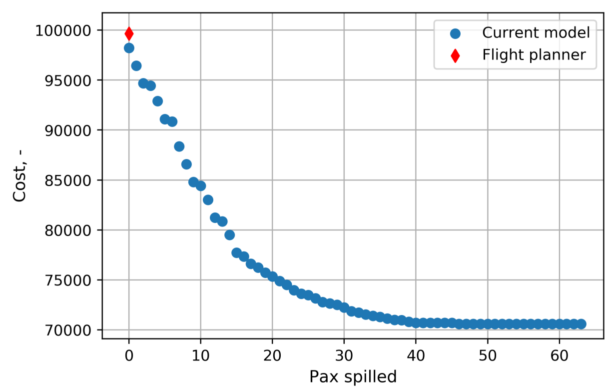

Fig. 14 Comparison of the results for 27-09-2019 made by the current model (daily optimization) and a human flight planner.

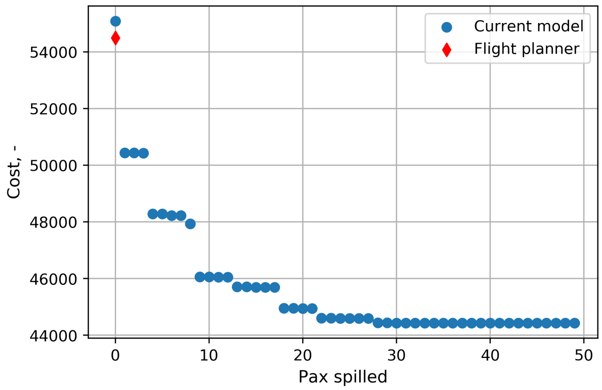

Fig. 15 Comparison of the results for 30-09-2019 made by the current model (daily optimization) and a human flight planner.

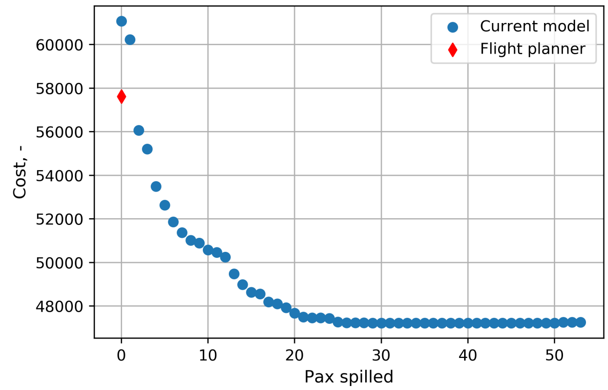

Fig. 16 Comparison of the results for 01-10-2019 made by the current model (daily optimization) and a human flight planner.

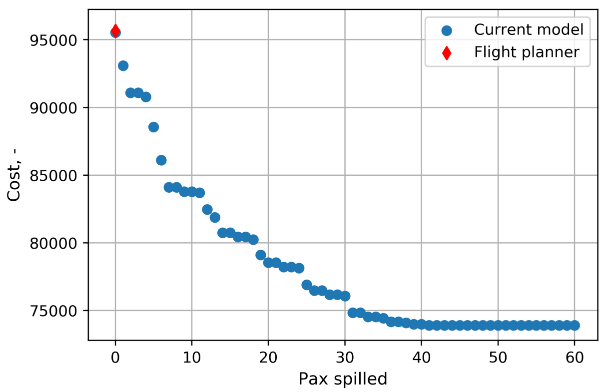

Fig. 17 Comparison of the results for 02-10-2019 made by the current model (daily optimization) and a human flight planner.

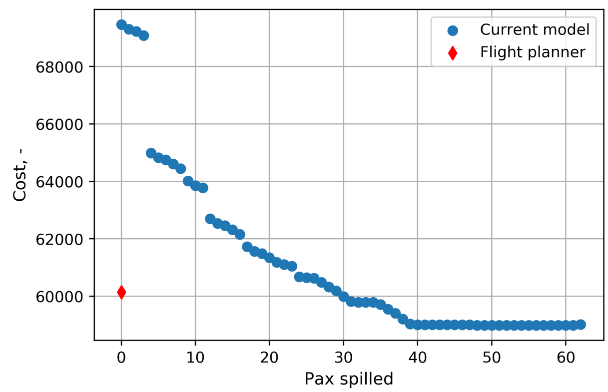

Fig. 18 Comparison of the results for 03-10-2019 made by the current model (daily optimization) and a human flight planner.

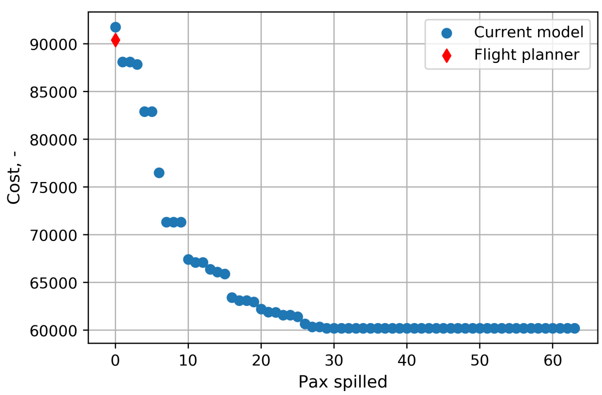

Fig. 19 Comparison of the results for 04-10-2019 made by the current model (daily optimization) and a human flight planner.

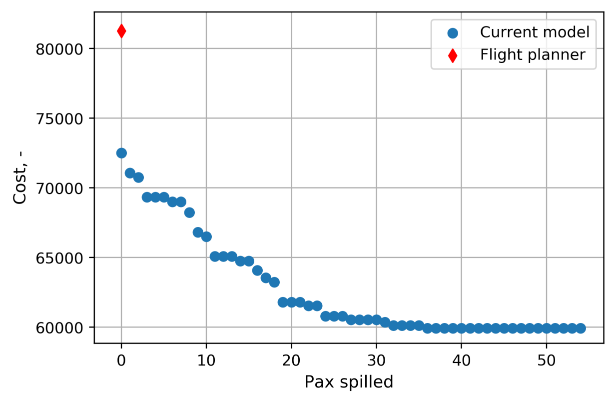

Fig. 20 Comparison of the results for 07-10-2019 made by the current model (daily optimization) and a human flight planner.

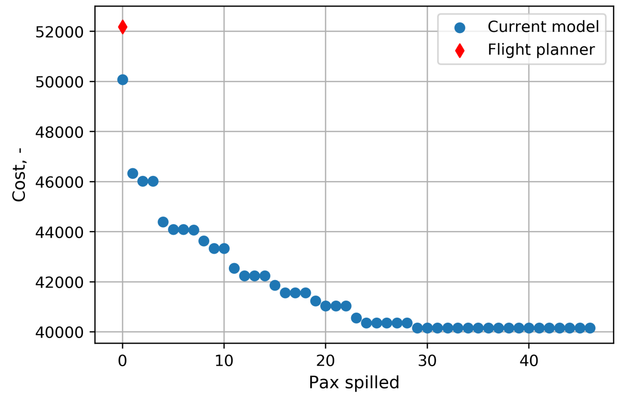

Fig. 21 Comparison of the results for 08-10-2019 made by the current model (daily optimization) and a human flight planner.

B. Monthly optimization

This section presents the results for the 2019 model when set for monthly optimization. The results of the human flight planner are also presented. It should be noted that the flight planner did consider the minimum guaranteed hours when planning his routes. Section E.B.1 provides the created Pareto fronts and Section E.B.2 shows the routes for 0 passengers spilled. All costs depicted in this section reflect block hour cost. For an analysis of the contract cost, the reader is referred to Section VI.B.

1. Pareto Fronts

Figures 22 till 32 show the Pareto fronts for the 2019 data. These figures result from the monthly optimization setting with 60 minimum guaranteed hours.

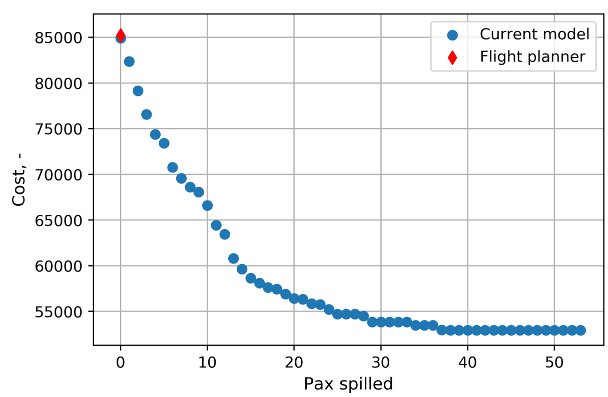

Fig. 22 Comparison of the results for 24-09-2019 made by the current model (monthly optimization, mgh=60) and a human flight planner.

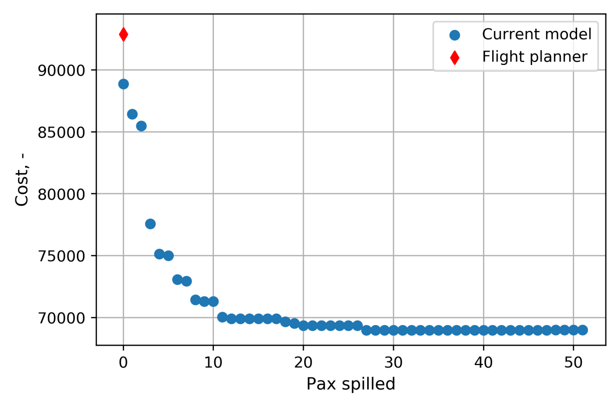

Fig. 23 Comparison of the results for 25-09-2019 made by the current model (monthly optimization, mgh=60) and a human flight planner.

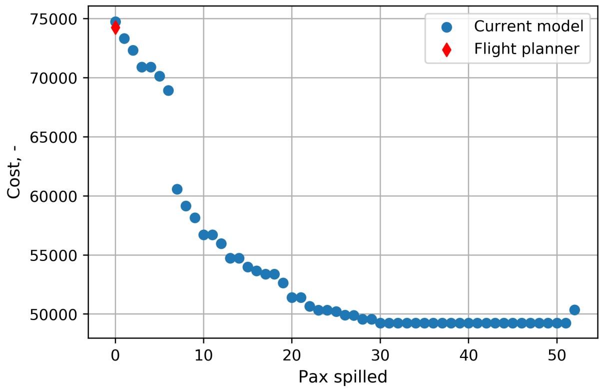

Fig. 24 Comparison of the results for 26-09-2019 made by the current model (monthly optimization, mgh=60) and a human flight planner.

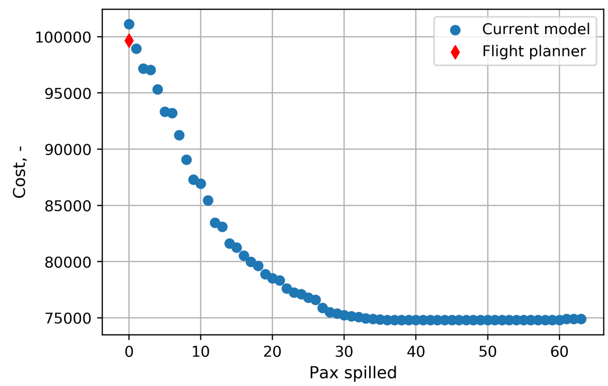

Fig. 25 Comparison of the results for 27-09-2019 made by the current model (monthly optimization, mgh=60) and a human flight planner.

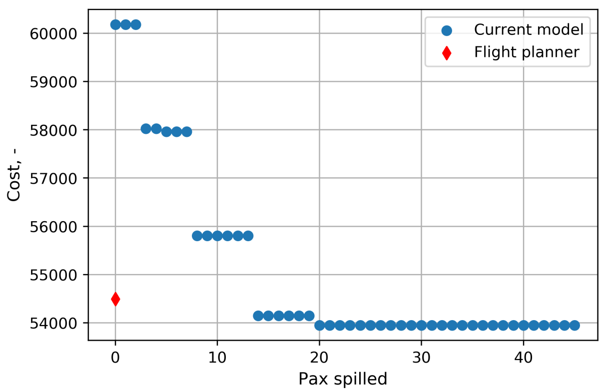

Fig. 26 Comparison of the results for 30-09-2019 made by the current model (monthly optimization, mgh=60) and a human flight planner.

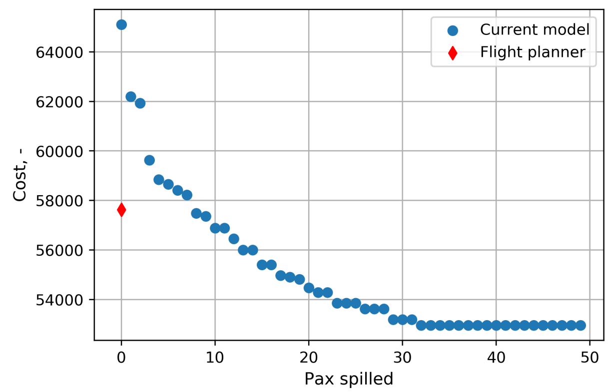

Fig. 27 Comparison of the results for 01-10-2019 made by the current model (monthly optimization, mgh=60) and a human flight planner.

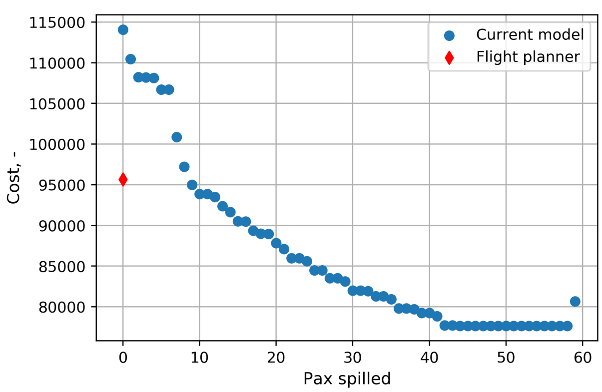

Fig. 28 Comparison of the results for 02-10-2019 made by the current model (monthly optimization, mgh=60) and a human flight planner.

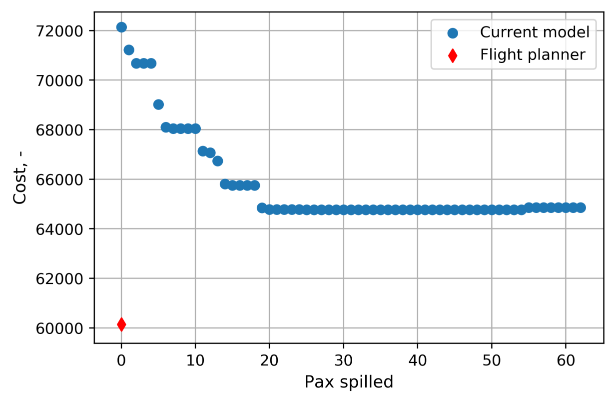

Fig. 29 Comparison of the results for 03-10-2019 made by the current model (monthly optimization, mgh=60) and a human flight planner.

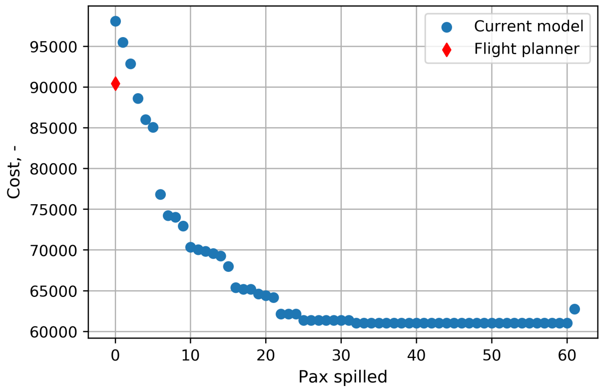

Fig. 30 Comparison of the results for 04-10-2019 made by the current model (monthly optimization, mgh=60) and a human flight planner.

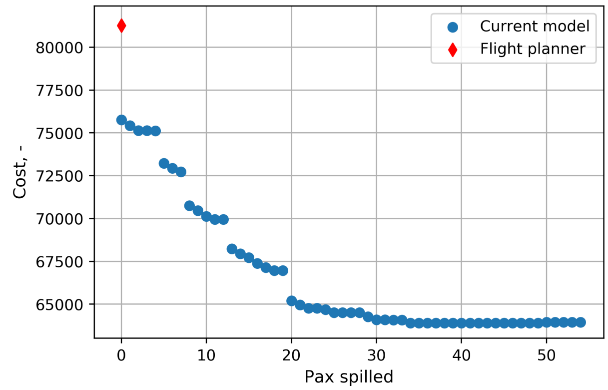

Fig. 31 Comparison of the results for 07-10-2019 made by the current model (monthly optimization, mgh=60) and a human flight planner.

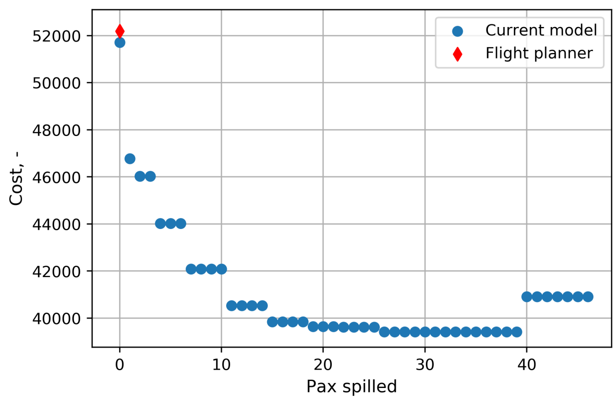

Fig. 32 Comparison of the results for 08-10-2019 made by the current model (monthly optimization, mgh=60) and a human flight planner.

2. Routes

Tables 20 till 30 show the constructed flight plans for the 2019 data for 100% demand satisfaction, resulting from the monthly optimizations setting with 60 minimum guaranteed hours.

Table 20 Overview of planned routes for 24-09-2019, resulting from the monthly optimization setting (mgh=60) and 100% demand satisfaction

aircraft	leg	origin	destination	pick-ups	deliveries	pax on leg	load factor	departure time	arrival time	block time [hr]	leg cost [-]	leg distance [nm]
Dash8Q	1	Juba (A)	Rumbek (A)	10 pax r37, 1 pax r18a, 1 pax r23a, 4 pax r24a, 8 pax r28a, 4 pax r33a, 1 pax r34a	10 pax r37, 1 pax r18a, 1 pax r23a, 4 pax r24a, 8 pax r28a, 4 pax r33a, 1 pax r34a	29	41%	7:30	8:04	0.57	3926.5	171.6
Dash8Q	2	Rumbek (A)	Juba (A)	8 pax r51, 3 pax r8b, 1 pax r46b	8 pax r51, 3 pax r8b, 1 pax r46b	12	17%	11:13	11:47	0.57	3926.5	171.6
Dash8_1	1	Juba (A)	Wau (A)	18 pax r20, 13 pax r38, 8 pax r17a, 2 pax r19a, 7 pax r30a	13 pax r38, 8 pax r17a, 2 pax r19a, 7 pax r30a	48	98%	7:15	8:13	0.97	3212.2	278.3
Dash8_1	2	Wau (A)	Aweil (A)	27 pax r53, 1 pax r2b, 1 pax r42b	18 pax r20	47	96%	11:28	11:43	0.25	832.4	72.1
Dash8_1	3	Aweil (A)	Rumbek (A)	8 pax r3		37	76%	13:16	13:52	0.61	2034.5	176.2
Dash8_1	4	Rumbek (A)	Juba (A)	1 pax r9b, 9 pax r15b, 1 pax r47b, 1 pax r52b	8 pax r3, 27 pax r53, 1 pax r2b, 1 pax r9b, 9 pax r15b, 1 pax r42b, 1 pax r47b, 1 pax r52b	49	100%	14:12	14:48	0.60	1980.5	171.6
Dash8_2	1	Juba (A)	Yei (A)	17 pax r40	17 pax r40	17	46%	8:45	8:59	0.24	655.4	68.9
Dash8_2	2	Yei (A)	Juba (A)	11 pax r54	11 pax r54	11	30%	9:19	9:33	0.24	655.4	68.9
Dornier_1	1	Juba (A)	Torit (A)	11 pax r27, 2 pax r29	11 pax r27	13	72%	8:30	8:51	0.36	860.2	61.6
Dornier_1	2	Torit (A)	Kapoeta (A)	6 pax r12, 2 pax r14	2 pax r14, 2 pax r29	10	56%	9:11	9:37	0.43	1015.7	72.8
Dornier_1	3	Kapoeta (A)	Juba (A)	1 pax r41	6 pax r12, 1 pax r41	7	39%	9:57	10:40	0.72	1707.2	122.3
Dornier_2	1	Juba (A)	Bor (A)	6 pax r22, 7 pax r31	6 pax r22	13	72%	8:00	8:28	0.48	1144.3	82
Dornier_2	2	Bor (A)	Mabior (A)	2 pax r6, 2 pax r5a	2 pax r6, 7 pax r31	11	61%	8:48	9:10	0.36	864.2	61.9
Dornier_2	3	Mabior (A)	Rumbek (A)	2 pax r43	2 pax r5a	4	22%	9:31	10:10	0.65	1539.8	110.3
Dornier_2	4	Rumbek (A)	Juba (A)		2 pax r43	2	11%	10:30	11:30	1.01	2394.8	171.6
Let_1	1	Juba (A)	Boma (A)	4 pax r21, 9 pax r35, 2 pax r36	4 pax r21	15	88%	7:45	8:50	1.09	2472	185.2
Let_1	2	Boma (A)	Pochalla (A)	4 pax r4	2 pax r36	15	88%	9:10	9:31	0.36	819.7	61.4
Let_1	3	Pochalla (A)	Pibor (A)	2 pax r50	9 pax r35	15	88%	9:51	10:13	0.37	838.2	62.8
Let_1	4	Pibor (A)	Bor (A)	1 pax r48, 6 pax r49	1 pax r48	13	76%	10:33	11:10	0.62	1400.3	104.9
Let_1	5	Bor (A)	Juba (A)		4 pax r4, 6 pax r49, 2 pax r50	12	71%	11:30	11:59	0.48	1094.1	82
Let_1	6	Juba (A)	Maridi (A)	2 pax r32	2 pax r32	2	12%	12:39	13:24	0.76	1718.6	128.8
Let_1	7	Maridi (A)	Mundri (A)	7 pax r44		7	41%	13:44	14:06	0.37	841	63
Let_1	8	Mundri (A)	Juba (A)	2 pax r45	7 pax r44, 2 pax r45	9	53%	14:26	14:55	0.49	1106.9	82.9
Let_2	1	Juba (A)	Malakal (A)	5 pax r25, 11 pax r26, 1 pax r39		17	100%	9:15	10:56	1.69	4249	288
Let_2	2	Malakal (A)	Renk (A)		11 pax r26	17	100%	11:16	12:04	0.81	2032.1	137.7
Let_2	3	Renk (A)	Paloich (P)	4 pax r11	5 pax r25	10	59%	12:24	12:47	0.38	947.7	64.2
Let_2	4	Paloich (P)	Walgal (A)	4 pax r10	1 pax r39	9	53%	13:07	13:57	0.83	2088.8	141.6
Let_2	5	Walgal (A)	Juba (A)		4 pax r10, 4 pax r11	8	47%	14:16	15:30	1.22	3069.6	208.1
Mi8_1	1	Juba (A)	Bor (A)	2 pax r16, 17 pax r39		19	100%	9:00	9:40	0.68	1955.1	82
Mi8_1	2	Bor (A)	Walgal (A)		17 pax r39	19	100%	10:00	11:06	1.09	3113.4	130.5
Mi8_1	3	Walgal (A)	Aburoc (H)		2 pax r16	2	11%	11:25	12:24	0.97	2775	116.4
Mi8_1	4	Aburoc (H)	Malakal (A)	4 pax r0, 1 pax r1	1 pax r1	5	26%	12:43	13:06	0.37	1048.4	44
Mi8_1	5	Malakal (A)	Juba (A)		4 pax r0	4	21%	13:25	15:49	2.40	6869	288
Cessna	1	Juba (A)	Rumbek (A)			0	0%	8:15	13:52	0.92	1154.8	171.6
Cessna	2	Rumbek (A)	Bor (A)	2 pax r13b	2 pax r13b	2	17%	14:12	14:51	0.65	819.1	121.7
Cessna	3	Bor (A)	Pibor (A)	1 pax r7	1 pax r7	1	8%	15:11	15:45	0.56	706.2	104.9
Cessna	4	Pibor (A)	Juba (A)			0	0%	16:04	16:53	0.81	1017.7	151.2
Mi8_1R	1	Rumbek (A)	Ganyiel (H)	1 pax r23b, 4 pax r24b, 4 pax r33b	4 pax r24b	9	47%	8:15	8:45	0.51	1460.5	61.2
Mi8_1R	2	Ganyiel (H)	Buot (H)	3 pax r8a	1 pax r23b	8	42%	9:05	9:34	0.48	1362	57.1
Mi8_1R	3	Buot (H)	Nyal (H)		4 pax r33b	7	37%	9:54	10:20	0.44	1266.4	53.1
Mi8_1R	4	Nyal (H)	Rumbek (A)	1 pax r46a	3 pax r8a, 1 pax r46a	4	21%	10:40	11:13	0.55	1583.4	66.4
Mi8_2R	1	Rumbek (A)	Gorwai (H)	2 pax r5b, 8 pax r28b, 1 pax r34b		11	58%	10:15	11:15	1	2350.2	120.1
Mi8_2R	2	Gorwai (H)	Wai (H)	1 pax r9a		12	63%	11:34	11:41	0.11	266.4	13.6
Mi8_2R	3	Wai (H)	Pagil (H)	1 pax r52a	1 pax r34b	13	68%	12:01	12:15	0.24	560.1	28.6
Mi8_2R	4	Pagil (H)	Jiech (H)	1 pax r47a	2 pax r5b, 8 pax r28b	13	68%	12:35	12:51	0.26	620	31.7
Mi8_2R	5	Jiech (H)	Rumbek (A)	2 pax r13a, 9 pax r15a	1 pax r9a, 2 pax r13a, 9 pax r15a, 1 pax r47a, 1 pax r52a	14	74%	13:10	14:12	1.03	2420.2	123.6
Cessna_1R	1	Rumbek (A)	Ajuong Thok (A)	1 pax r18b	1 pax r18b	1	8%	8:30	9:31	1.03	1287.7	191.3
Cessna_1R	2	Ajuong Thok (A)	Rumbek (A)			0	0%	9:51	10:53	1.03	1287.7	191.3
Cessna_1W	1	Wau (A)	Kuajok (A)	7 pax r30b	7 pax r30b	7	58%	8:45	8:54	0.16	181.7	30.4
Cessna_1W	2	Kuajok (A)	Wau (A)	1 pax r42a	1 pax r42a	1	8%	9:14	9:24	0.16	181.7	30.4
Cessna_1W	3	Wau (A)	Agok (A)	8 pax r17b, 2 pax r19b	8 pax r17b	10	83%	9:43	10:16	0.54	596.9	99.9
Cessna_1W	4	Agok (A)	Alek (A)		2 pax r19b	2	17%	10:36	10:50	0.24	271.9	45.5
Cessna_1W	5	Alek (A)	Wau (A)	1 pax r2a	1 pax r2a	1	8%	11:10	11:28	0.31	341.4	57.1

Table 21 Overview of planned routes for 25-09-2019, resulting from the monthly optimization setting (mgh=60) and 100% demand satisfaction

aircraft	leg	origin	destination	pick-ups	deliveries	pax on leg	load factor	departure time	arrival time	block time [hr]	leg cost [-]	leg distance [nm]
Dash8Q	1	Juba (A)	Rumbek (A)	8 pax r12, 6 pax r9a, 8 pax r10a	8 pax r12, 6 pax r9a, 8 pax r10a	22	31%	7:30	8:04	0.57	3926.5	171.6
Dash8Q	2	Rumbek (A)	Juba (A)	15 pax r28	15 pax r28	15	21%	8:30	9:04	0.57	3926.5	171.6
Dash8_1	1	Juba (A)	Rubkona (A)	21 pax r11	21 pax r11	21	43%	8:30	9:30	1.01	3356.7	290.8
Dash8_1	2	Rubkona (A)	Juba (A)	15 pax r27	15 pax r27	15	31%	9:50	10:51	1.01	3356.7	290.8
Dash8_1	3	Juba (A)	Malakal (A)	36 pax r7, 9 pax r8	9 pax r8	45	92%	11:10	12:10	1.00	3324.7	288.0
Dash8_1	4	Malakal (A)	Maban (A)	12 pax r22	36 pax r7	48	98%	12:30	12:56	0.43	1436.8	124.5
Dash8_1	5	Maban (A)	Juba (A)	15 pax r21	15 pax r21, 12 pax r22	27	55%	13:16	14:25	1.16	3828.4	331.6
Dash8_2	1	Juba (A)	Wau (A)	24 pax r15, 6 pax r18a	24 pax r15, 6 pax r18a	30	81%	7:15	8:12	0.96	2645	278.3
Dash8_2	2	Wau (A)	Rumbek (A)	11 pax r31, 7 pax r34b		18	49%	12:39	13:02	0.38	1036.6	109.1
Dash8_2	3	Rumbek (A)	Juba (A)	1 pax r20b, 2 pax r24b, 4 pax r25b	11 pax r31, 1 pax r20b, 2 pax r24b, 4 pax r25b, 7 pax r34b	37	100%	13:22	13:57	0.59	1630.8	171.6
Dash8_2	4	Juba (A)	Yei (A)	12 pax r16, 1 pax r17	1 pax r17	13	35%	14:37	14:51	0.24	655.4	68.9
Dash8_2	5	Yei (A)	Yambio (A)		12 pax r16	12	32%	15:11	15:40	0.48	1313.7	138.2
Dash8_2	6	Yambio (A)	Juba (A)	16 pax r33	16 pax r33	16	43%	16:00	16:40	0.67	1834.1	193.0
Cessna	1	Juba (A)	Tambura (A)	9 pax r13	9 pax r13	9	75%	8:45	10:05	1.34	1683.7	250.1
Cessna	2	Tambura (A)	Juba (A)	11 pax r29	11 pax r29	11	92%	10:25	11:45	1.34	1683.7	250.1
Cessna	3	Juba (A)	Torit (A)	2 pax r5	2 pax r5	2	17%	12:05	12:25	0.33	414.8	61.6
Cessna	4	Torit (A)	Juba (A)	7 pax r2	7 pax r2	7	58%	12:45	13:04	0.33	414.8	61.6
Cessna	5	Juba (A)	Kuron (H)	8 pax r6	8 pax r6	8	67%	13:44	15:00	1.26	1573.6	233.8
Cessna	6	Kuron (H)	Juba (A)	8 pax r19	8 pax r19	8	67%	15:19	16:35	1.26	1573.6	233.8
Mi8_1	1	Juba (A)	Bor (A)	18 pax r4	18 pax r4	18	95%	9:00	9:40	0.68	1955.1	82.0
Mi8_1	2	Bor (A)	Mingkaman (H)	2 pax r1		2	11%	10:00	10:03	0.05	142.5	6.0
Mi8_1	3	Mingkaman (H)	Juba (A)	2 pax r23	2 pax r1, 2 pax r23	19	100%	10:23	11:01	0.64	1828.5	76.7
Dornier_1	1	Juba (A)	Malakal (A)	18 pax r8	18 pax r8	18	100%	8:15	9:56	1.69	4020.3	288.0
Dornier_1	2	Malakal (A)	Juba (A)			18	100%	10:16	11:57	1.69	4020.3	288.0
Dornier_2	1	Juba (A)	Ulang (A)	5 pax r14	5 pax r14	5	28%	7:45	9:11	1.44	3420.9	245.1
Dornier_2	2	Ulang (A)	Bor (A)	13 pax r30		18	100%	9:31	10:31	1.00	2381.6	170.6
Dornier_2	3	Bor (A)	Juba (A)		13 pax r30	18	100%	10:51	11:19	0.48	1144.3	82.0
Mi8_2	1	Juba (A)	Malakal (A)	16 pax r3		16	84%	8:00	10:24	2.40	8311.5	288.0
Mi8_2	2	Malakal (A)	Ajuong Thok (A)	2 pax r22	16 pax r3	18	95%	10:43	11:25	0.69	2388.4	82.8
Mi8_2	3	Ajuong Thok (A)	Juba (A)	17 pax r0	17 pax r0, 2 pax r22	19	100%	11:45	14:25	2.67	9244.8	320.4
Mi8_2R	1	Rumbek (A)	Kurwai (H)	6 pax r9b, 8 pax r10b		14	74%	8:15	9:40	1.43	3351.5	171.2
Mi8_2R	2	Kurwai (H)	New Fankgak (A)	1 pax r20a	6 pax r9b	15	79%	10:00	10:03	0.05	107.4	5.5
Mi8_2R	3	New Fankgak (A)	Old Fangak (A)	2 pax r24a	8 pax r10b	11	58%	10:23	10:31	0.14	334.1	17.1
Mi8_2R	4	Old Fangak (A)	Rumbek (A)	4 pax r25a	1 pax r20a, 2 pax r24a, 4 pax r25a	7	37%	10:51	12:08	1.28	2998.2	153.2
Cessna_1W	1	Wau (A)	Yida (A)	1 pax r32, 6 pax r18b	6 pax r18b	7	58%	8:45	9:45	1.00	1110	185.8
Cessna_1W	2	Yida (A)	Raja (A)	7 pax r34a	1 pax r32	8	67%	10:04	11:33	1.48	1641.6	274.8
Cessna_1W	3	Raja (A)	Wau (A)	2 pax r26	2 pax r26, 7 pax r34a	9	75%	11:53	12:39	0.77	860.5	144.1

Table 22 Overview of planned routes for 26-09-2019, resulting from the monthly optimization setting (mgh=60) and 100% demand satisfaction

aircraft	leg	origin	destination	pick-ups	deliveries	pax on leg	load factor	departure time	arrival time	block time [hr]	leg cost [-]	leg distance [nm]
Dash8Q	1	Juba (A)	Wau (A)	9 pax r10, 18 pax r27, 10 pax r8a, 4 pax r9a, 10 pax r21a, 5 pax r22a	18 pax r27, 10 pax r8a, 4 pax r9a, 10 pax r21a, 5 pax r22a	56	79%	7:30	8:25	0.93	6368.7	278.3
Dash8Q	2	Wau (A)	Aweil (A)	2 pax r39, 17 pax r40, 7 pax r0b, 7 pax r33b, 2 pax r34b	9 pax r10, 2 pax r39	44	62%	13:21	13:35	0.24	1650.4	72.1
Dash8Q	3	Aweil (A)	Rumbek (A)	9 pax r1		42	59%	13:55	14:30	0.59	4033.8	176.2
Dash8Q	4	Rumbek (A)	Juba (A)	13 pax r37, 7 pax r32b, 5 pax r42b	9 pax r1, 13 pax r37, 17 pax r40, 7 pax r0b, 7 pax r32b, 7 pax r33b, 2 pax r34b, 5 pax r42b	67	94%	14:50	15:24	0.57	3926.5	171.6
Dash8_2	1	Juba (A)	Rumbek (A)	4 pax r26, 1 pax r12a, 5 pax r20a, 9 pax r29a	4 pax r26, 1 pax r12a, 5 pax r20a, 9 pax r29a	19	51%	7:15	7:50	0.59	1630.8	171.6
Dash8_2	2	Rumbek (A)	Juba (A)			0	0%	8:45	9:20	0.59	1630.8	171.6
Dash8_2	3	Juba (A)	Yei (A)	4 pax r28	4 pax r28	4	11%	9:40	9:54	0.24	655.4	68.9
Dash8_2	4	Yei (A)	Juba (A)	14 pax r41	14 pax r41	14	38%	10:14	10:28	0.24	655.4	68.9
Cessna	1	Juba (A)	Rumbek (A)	6 pax r11, 2 pax r25		8	67%	10:52	11:47	0.92	1154.8	171.6
Cessna	2	Rumbek (A)	Bor (A)	1 pax r38b	6 pax r11, 1 pax r38b	9	75%	12:07	12:46	0.65	819.1	121.7
Cessna	3	Bor (A)	Pochalla (A)	8 pax r2	2 pax r25	10	83%	13:06	14:00	0.90	1128.9	167.7
Cessna	4	Pochalla (A)	Juba (A)	1 pax r36	8 pax r2, 1 pax r36	9	75%	14:19	15:27	1.12	1400.6	208.1
Dornier_1	1	Juba (A)	Akobo (A)	8 pax r13, 4 pax r14, 3 pax r15	8 pax r13	15	83%	8:00	9:09	1.15	2736.7	196.1
Dornier_1	2	Akobo (A)	Renk (A)	5 pax r3	3 pax r15	12	67%	9:28	10:49	1.34	3171.8	227.2
Dornier_1	3	Renk (A)	Paloich (P)	2 pax r5	4 pax r14	11	61%	11:09	11:31	0.38	896.7	64.2
Dornier_1	4	Paloich (P)	Malakal (A)	7 pax r4		14	78%	11:51	12:18	0.45	1065.3	76.3
Dornier_1	5	Malakal (A)	Juba (A)		5 pax r3, 7 pax r4, 2 pax r5	14	78%	12:38	14:19	1.69	4020.3	288.0
Dornier_1	6	Juba (A)	Kajo Keji (A)	3 pax r16, 6 pax r19	6 pax r19	9	50%	14:59	15:21	0.36	849.5	60.9
Dornier_1	7	Kajo Keji (A)	Torit (A)	1 pax r31	3 pax r16	4	22%	15:40	16:01	0.34	817.8	58.6
Dornier_1	8	Torit (A)	Juba (A)	17 pax r6	17 pax r6, 1 pax r31	18	100%	16:21	16:42	0.36	860.2	61.6
Dornier_2	1	Juba (A)	Kapoeta (A)	7 pax r18, 11 pax r24	7 pax r18	18	100%	8:15	8:58	0.72	1707.2	122.3
Dornier_2	2	Kapoeta (A)	Nimule (A)	4 pax r30	11 pax r24	15	83%	9:18	9:58	0.68	1621.9	116.2
Dornier_2	3	Nimule (A)	Juba (A)		4 pax r30	4	22%	10:18	10:45	0.44	1051.6	75.3
Mi8_2	1	Juba (A)	Bor (A)	7 pax r17, 2 pax r23		9	47%	7:45	8:25	0.68	2365.6	82.0
Mi8_2	2	Bor (A)	Malakal (A)			9	47%	8:45	10:28	1.72	5952.2	206.3
Mi8_2	3	Malakal (A)	Mathiang (H)		2 pax r23	9	47%	10:48	11:46	0.97	3361.6	116.5
Mi8_2	4	Mathiang (H)	Jikmir (A)	5 pax r35	7 pax r17	12	63%	12:06	12:27	0.34	1176.5	40.8
Mi8_2	5	Jikmir (A)	Juba (A)	9 pax r7	9 pax r7, 5 pax r35	14	74%	12:46	14:45	1.97	6829.9	236.7
Mi8_1R	1	Rumbek (A)	Koch (H)	1 pax r12b, 5 pax r20b	5 pax r20b	6	32%	8:30	9:23	0.89	2546.5	106.8
Mi8_1R	2	Koch (H)	Wai (H)	7 pax r32a		8	42%	9:43	10:21	0.64	1819.8	76.3
Mi8_1R	3	Wai (H)	Buot (H)	1 pax r38a	1 pax r12b	9	47%	10:41	10:48	0.12	348.4	14.6
Mi8_1R	4	Buot (H)	Rumbek (A)		7 pax r32a, 1 pax r38a	8	42%	11:08	12:07	0.98	2799.8	117.4
Cessna_1R	1	Rumbek (A)	Yirol (A)	9 pax r29b	9 pax r29b	9	75%	8:15	8:33	0.31	389.5	57.9
Cessna_1R	2	Yirol (A)	Rumbek (A)	5 pax r42a	5 pax r42a	5	42%	8:53	9:12	0.31	389.5	57.9
Cessna_1W	1	Wau (A)	Kuajok (A)	10 pax r21b	10 pax r21b	10	83%	8:45	8:54	0.16	181.7	30.4
Cessna_1W	2	Kuajok (A)	Wau (A)	7 pax r33a	7 pax r33a	7	58%	9:14	9:24	0.16	181.7	30.4
Cessna_1W	3	Wau (A)	Alek (A)	4 pax r9b, 5 pax r22b	4 pax r9b	9	75%	9:43	10:02	0.31	341.4	57.1
Cessna_1W	4	Alek (A)	Mankien (A)		5 pax r22b	5	42%	10:22	10:43	0.35	390.0	65.3
Cessna_1W	5	Mankien (A)	Wau (A)	2 pax r34a	2 pax r34a	2	17%	11:03	11:36	0.56	617.7	103.4
Cessna_1W	6	Wau (A)	Agok (A)	10 pax r8b	10 pax r8b	10	83%	11:56	12:28	0.54	596.9	99.9
Cessna_1W	7	Agok (A)	Wau (A)	7 pax r0a	7 pax r0a	7	58%	12:48	13:21	0.54	596.9	99.9

Table 23 Overview of planned routes for 27-09-2019, resulting from the monthly optimization setting (mgh=60) and 100% demand satisfaction.

aircraft	leg	origin	destination	pick-ups	deliveries	pax on leg	load factor	departure time	arrival time	block time [hr]	leg cost [-]	leg distance [nm]
Dash8Q	1	Juba (A)	Rumbek (A)	8 pax r11, 16 pax r29, 6 pax r32, 5 pax r13a, 1 pax r15a, 3 pax r18a, 4 pax r19a, 6 pax r22a, 6 pax r24a, 7 pax r25a, 7 pax r30a	16 pax r29, 5 pax r13a, 1 pax r15a, 3 pax r18a, 4 pax r19a, 6 pax r22a, 6 pax r24a, 7 pax r25a, 7 pax r30a	69	97%	7:30	8:04	0.57	3926.5	171.6
Dash8Q	2	Rumbek (A)	Aweil (A)	16 pax r49, 9 pax r5b, 4 pax r38b, 8 pax r39b, 1 pax r43b, 3 pax r45b, 2 pax r50b	8 pax r11	57	80%	13:00	13:35	0.59	4033.8	176.2
Dash8Q	3	Aweil (A)	Wau (A)	20 pax r2, 2 pax r3	2 pax r3, 6 pax r32	71	100%	13:55	14:09	0.24	1650.4	72.1
Dash8Q	4	Wau (A)	Juba (A)	1 pax r52, 2 pax r0b, 5 pax r57b	20 pax r2, 16 pax r49, 1 pax r52, 2 pax r0b, 9 pax r5b, 4 pax r38b, 8 pax r39b, 1 pax r43b, 3 pax r45b, 2 pax r50b, 5 pax r57b	71	100%	14:29	15:25	0.93	6368.7	278.3
Dash8_1	1	Juba (A)	Rubkona (A)	24 pax r21, 25 pax r28	25 pax r28	49	100%	8:30	9:30	1.01	3356.7	290.8
Dash8_1	2	Rubkona (A)	Malakal (A)	21 pax r48	24 pax r21	45	92%	9:50	10:13	0.39	1292.9	112.0
Dash8_1	3	Malakal (A)	Juba (A)	25 pax r42	25 pax r42, 21 pax r48	46	94%	10:33	11:33	1.00	3324.7	288.0
Dash8_2	1	Juba (A)	Wau (A)	12 pax r32, 5 pax r9a, 9 pax r36a	12 pax r32, 5 pax r9a, 9 pax r36a	26	70%	7:15	8:12	0.96	2645.0	278.3
Dash8_2	2	Wau (A)	Juba (A)	22 pax r52	22 pax r52	22	59%	9:00	9:57	0.96	2645.0	278.3
Dash8_2	3	Juba (A)	Maban (A)	13 pax r20	13 pax r20	13	35%	10:37	11:46	1.15	3152.4	331.6
Dash8_2	4	Maban (A)	Juba (A)	19 pax r41	19 pax r41	19	51%	12:06	13:15	1.15	3152.4	331.6
Dash8_2	5	Juba (A)	Yambio (A)	22 pax r34, 1 pax r35	22 pax r34	23	62%	13:54	14:34	0.67	1834.1	193.0
Dash8_2	6	Yambio (A)	Yei (A)	16 pax r55	1 pax r35	17	46%	14:54	15:23	0.48	1313.7	138.2
Dash8_2	7	Yei (A)	Juba (A)	2 pax r56	16 pax r55, 2 pax r56	18	49%	15:43	15:57	0.24	655.4	68.9
Cessna	1	Juba (A)	Kapoeta (A)	2 pax r14, 2 pax r16	2 pax r16	4	33%	8:15	8:54	0.66	823.2	122.3
Cessna	2	Kapoeta (A)	Torit (A)		2 pax r14	2	17%	9:14	9:37	0.39	489.8	72.8
Cessna	3	Torit (A)	Juba (A)	1 pax r8	1 pax r8	1	8%	9:57	10:17	0.33	414.8	61.6
Cessna	4	Juba (A)	Paloich (P)	6 pax r21		6	50%	10:57	12:49	1.88	2348.8	348.9
Cessna	5	Paloich (P)	Renk (A)	1 pax r7	1 pax r7	12	100%	13:09	13:30	0.35	432.4	64.2
Cessna	6	Renk (A)	Malakal (A)		6 pax r21	11	92%	13:50	14:34	0.74	927.2	137.7
Cessna	7	Malakal (A)	Juba (A)			12	100%	14:54	16:27	1.55	1938.6	288.0
Dornier_1	1	Juba (A)	Wanding (A)	4 pax r31		4	22%	8:00	9:15	1.26	2993.8	214.5
Dornier_1	2	Wanding (A)	Ulang (A)	5 pax r54	4 pax r31	9	50%	9:35	9:49	0.24	558.2	40.0
Dornier_1	3	Ulang (A)	Juba (A)	13 pax r51	13 pax r51, 5 pax r54	18	100%	10:09	11:36	1.44	3420.9	245.1
Dornier_1	4	Juba (A)	Pibor (A)	18 pax r26	18 pax r26	18	100%	12:15	13:09	0.89	2110.5	151.2
Dornier_1	5	Pibor (A)	Bor (A)	1 pax r46, 14 pax r47	1 pax r46	15	83%	13:28	14:06	0.62	1464.5	104.9
Dornier_1	6	Bor (A)	Juba (A)	4 pax r4	4 pax r4, 14 pax r47	18	100%	14:25	14:54	0.48	1144.3	82.0
Mi8_1	1	Juba (A)	Bor (A)	1 pax r17, 1 pax r27, 2 pax r33		4	21%	7:45	8:25	0.68	1955.1	82.0
Mi8_1	2	Bor (A)	Karam (A)		1 pax r17	4	21%	8:45	9:47	1.03	2955.7	123.9
Mi8_1	3	Karam (A)	Wiechjol LZ (H)	2 pax r37	2 pax r33	5	26%	10:07	10:19	0.21	590.1	24.7
Mi8_1	4	Wiechjol LZ (H)	Pieri (A)	3 pax r53	1 pax r27	6	32%	10:39	10:45	0.09	269.1	11.3
Mi8_1	5	Pieri (A)	Juba (A)		2 pax r37, 3 pax r53	19	100%	11:04	12:41	1.61	4602.0	193.0
Let_1	1	Juba (A)	Bor (A)	15 pax r10		15	88%	8:45	9:13	0.48	1094.1	82.0
Let_1	2	Bor (A)	Malakal (A)			15	88%	9:33	10:46	1.21	2752.9	206.3
Let_1	3	Malakal (A)	Ajuong Thok (A)	2 pax r42	15 pax r10	17	100%	11:06	11:35	0.49	1104.6	82.8
Let_1	4	Ajuong Thok (A)	Juba (A)	15 pax r1	15 pax r1, 2 pax r42	17	100%	11:55	13:48	1.88	4275.7	320.4
Let_1	5	Juba (A)	Bor (A)	16 pax r12	16 pax r12	16	94%	14:27	14:56	0.48	1094.1	82.0
Let_1	6	Bor (A)	Juba (A)	17 pax r4	17 pax r4	17	100%	15:16	15:45	0.48	1094.1	82.0
Mi8_1	1	Juba (A)	Mingkaman (H)	2 pax r23	2 pax r23	2	11%	13:21	13:59	0.64	1828.5	76.7
Mi8_1	2	Mingkaman (H)	Bor (A)	1 pax r44		17	89%	14:19	14:22	0.05	142.5	6.0
Mi8_1	3	Bor (A)	Juba (A)	2 pax r4	2 pax r4, 1 pax r44	19	100%	14:42	15:22	0.68	1955.1	82.0
Mi8_1R	1	Rumbek (A)	Jiech (H)	2 pax r13b, 1 pax r15b, 4 pax r19b, 7 pax r25b	1 pax r15b	14	74%	8:45	9:46	1.03	2948.7	123.6
Mi8_1R	2	Jiech (H)	Lankien (H)		4 pax r19b	13	68%	10:06	10:34	0.46	1307.6	54.8
Mi8_1R	3	Lankien (H)	Palouny (H)	8 pax r39a	7 pax r25b	19	100%	10:54	11:12	0.31	893.3	37.5
Mi8_1R	4	Palouny (H)	Ganyiel (H)		2 pax r13b	12	63%	11:32	12:09	0.62	1783.1	74.8
Mi8_1R	5	Ganyiel (H)	Rumbek (A)	9 pax r5a	9 pax r5a, 8 pax r39a	19	100%	12:29	13:00	0.51	1460.5	61.2
Mi8_2R	1	Rumbek (A)	Ganyiel (H)	3 pax r13b, 3 pax r18b, 6 pax r24b, 7 pax r30b	3 pax r13b	19	100%	8:30	9:00	0.51	1198.7	61.2
Mi8_2R	2	Ganyiel (H)	Nyal (H)	2 pax r6	2 pax r6, 6 pax r24b	18	95%	9:20	9:30	0.16	375.1	19.2
Mi8_2R	3	Nyal (H)	Touch Riak (H)	3 pax r45a	7 pax r30b	13	68%	9:49	10:01	0.20	473.3	24.2
Mi8_2R	4	Touch Riak (H)	Leer (H)	2 pax r50a	3 pax r18b	8	42%	10:21	10:28	0.11	259.8	13.3
Mi8_2R	5	Leer (H)	Rumbek (A)	4 pax r38a	4 pax r38a, 3 pax r45a, 2 pax r50a	19	100%	10:48	11:33	0.75	1756.6	89.7
Cessna_1R	1	Rumbek (A)	Mayendit (A)	6 pax r22b	6 pax r22b	6	50%	8:15	8:42	0.45	561.5	83.4
Cessna_1R	2	Mayendit (A)	Rumbek (A)	1 pax r43a	1 pax r43a	1	8%	9:01	9:28	0.45	561.5	83.4
Cessna_1W	1	Wau (A)	Agok (A)	5 pax r9b	5 pax r9b	5	42%	8:45	9:17	0.54	596.9	99.9
Cessna_1W	2	Agok (A)	Wau (A)	2 pax r0a	2 pax r0a	2	17%	9:37	10:09	0.54	596.9	99.9
Cessna_1W	3	Wau (A)	Yida (A)	9 pax r36b	9 pax r36b	9	75%	10:29	11:29	1.00	1110.0	185.8
Cessna_1W	4	Yida (A)	Wau (A)	5 pax r57a	5 pax r57a	5	42%	11:49	12:49	1.00	1110.0	185.8

Table 24 Overview of planned routes for 30-09-2019, resulting from the monthly optimization setting (mgh=60) and 100% demand satisfaction.

aircraft	leg	origin	destination	pick-ups	deliveries	pax on leg	load factor	departure time	arrival time	block time	leg cost	leg distance
Dash8Q	1	Juba (A)	Rumbek (A)	24 pax r12, 3 pax r7a, 12 pax r8a, 6 pax r11a	24 pax r12, 3 pax r7a, 12 pax r8a, 6 pax r11a	45	63%	07:30	08:04	0.57	3926.5	171.6
Dash8Q	2	Rumbek (A)	Juba (A)	8 pax r21	8 pax r21	8	11%	09:00	09:34	0.57	3926.5	171.6
Dash8_1	1	Juba (A)	Malakal (A)	29 pax r9	29 pax r9	29	59%	08:15	09:15	1	3324.7	288
Dash8_1	2	Malakal (A)	Juba (A)	13 pax r19	13 pax r19	13	27%	09:34	10:34	1	3324.7	288
Dash8_2	1	Juba (A)	Wau (A)	22 pax r13, 4 pax r15a	22 pax r13, 4 pax r15a	26	70%	07:15	08:45	0.96	2645	278.3
Dash8_2	2	Wau (A)	Rumbek (A)	17 pax r22, 1 pax r24b		18	49%	11:04	11:27	0.38	1036.6	109.1
Dash8_2	3	Rumbek (A)	Juba (A)	4 pax r18b	17 pax r22, 4 pax r18b, 1 pax r24b	22	59%	11:47	12:22	0.59	1630.8	171.6
Dash8_2	4	Juba (A)	Yambio (A)	29 pax r14	29 pax r14	29	78%	13:02	13:42	0.67	1834.1	193
Dash8_2	5	Yambio (A)	Juba (A)	15 pax r23	15 pax r23	15	41%	14:02	14:42	0.67	1834.1	193
Let_1	1	Juba (A)	Bor (A)	12 pax r3		12	71%	10:25	10:54	0.48	1094.1	82
Let_1	2	Bor (A)	Malakal (A)			12	71%	11:14	12:27	1.21	2752.9	206.3
Let_1	3	Malakal (A)	Ajuong Thok (A)	12 pax r3	12	71%	12:46	13:16	0.49	1104.6	82.8	
Let_1	4	Ajuong Thok (A)	Bor (A)	13 pax r0		13	76%	13:36	15:00	1.41	3208	240.4
Let_1	5	Bor (A)	Juba (A)		13 pax r0	13	76%	15:20	15:49	0.48	1094.1	82
Let_1	6	Juba (A)	Kapoeta (A)	11 pax r6	11 pax r6	11	65%	08:00	08:43	0.72	1632.4	122.3
Let_1	7	Kapoeta (A)	Juba (A)	6 pax r16	6 pax r16	6	35%	09:03	09:46	0.72	1632.4	122.3
Let_2	1	Juba (A)	Torit (A)	12 pax r5	12 pax r5	12	71%	07:45	08:06	0.36	909.1	61.6
Let_2	2	Torit (A)	Juba (A)	7 pax r2	7 pax r2	7	41%	08:26	08:48	0.36	909.1	61.6
Let_2	3	Juba (A)	Bor (A)	9 pax r4	9 pax r4	9	53%	09:27	09:56	0.48	1209.4	82
Let_2	4	Bor (A)	Juba (A)			0	0%	10:16	10:45	0.48	1209.4	82
Mi8_1	1	Juba (A)	Mingkaman (H)	11 pax r4, 8 pax r10	8 pax r10	19	100%	08:30	09:08	0.64	1828.5	76.7
Mi8_1	2	Mingkaman (H)	Bor (A)	2 pax r20	11 pax r4	13	68%	09:38	09:41	0.05	142.5	6
Mi8_1	3	Bor (A)	Juba (A)	15 pax r1	15 pax r1, 2 pax r20	17	89%	10:01	10:42	0.68	1955.1	82
Mi8_1R	1	Rumbek (A)	Leer (H)	6 pax r11b		6	32%	08:45	09:30	0.75	2140.3	89.7
Mi8_1R	2	Leer (H)	Padeah (H)	9 pax r17	6 pax r11b	15	79%	09:49	09:54	0.07	197.2	8.3
Mi8_1R	3	Padeah (H)	Dindin (A)		9 pax r17	9	47%	10:13	10:20	0.11	302.6	12.7
Mi8_1R	4	Dindin (A)	Rumbek hub end			0	0%	10:40	11:26	0.77	2210.1	92.7
Mi8_2R	1	Rumbek (A)	Lankien (H)	12 pax r8b	12 pax r8b	12	63%	08:30	09:56	1.44	3394.2	173.4
Mi8_2R	2	Lankien (H)	Rumbek (A)	4 pax r18a	4 pax r18a	4	21%	10:16	11:42	1.44	3394.2	173.4
Cessna_1R	1	Rumbek (A)	Keew (A)	3 pax r7b	3 pax r7b	3	25%	08:15	09:06	0.86	1079.1	160.3
Cessna_1R	2	Keew (A)	Rumbek hub end			0	0%	09:26	10:18	0.86	1079.1	160.3
Cessna_1W	1	Wau (A)	Yida (A)	4 pax r15b	4 pax r15b	4	33%	08:45	09:45	1	1110	185.8
Cessna_1W	2	Yida (A)	Wau (A)	1 pax r24a	1 pax r24a	1	8%	10:04	11:04	1	1110	185.8

Table 25 Overview of planned routes for 01-10-2019, resulting from the monthly optimization setting (mgh=60) and 100% demand satisfaction.

aircraft	leg	origin	destination	pick-ups	deliveries	pax on leg	load factor	departure time	arrival time	block time [hr]	leg cost [-]	leg distance [nm]
Dash8Q	1	Juba (A)	Rumbek (A)	24 pax r26, 5 pax r12a, 5 pax r16a, 1 pax r20a, 2 pax r22a, 1 pax r23a	24 pax r26, 5 pax r12a, 5 pax r16a, 1 pax r20a, 2 pax r22a, 1 pax r23a	38	54%	7:30	8:15	0.57	3926.5	171.6
Dash8Q	2	Rumbek (A)	Juba (A)	7 pax r39, 3 pax r3b, 4 pax r5b, 1 pax r9b, 4 pax r33b, 1 pax r34b	7 pax r39, 3 pax r3b, 4 pax r5b, 1 pax r9b, 4 pax r33b, 1 pax r34b	20	28%	15:45	16:19	0.57	3926.5	171.6
Dash8_1	1	Juba (A)	Wau (A)	13 pax r27, 10 pax r10a	13 pax r27, 10 pax r10a	23	47%	7:45	8:43	0.97	3212.2	278.3
Dash8_1	2	Wau (A)	Juba (A)	16 pax r40, 8 pax r0b	16 pax r40, 8 pax r0b	24	49%	10:09	11:07	0.97	3212.2	278.3
Dash8_2	1	Juba (A)	Yei (A)	16 pax r28	16 pax r28	16	43%	8:15	8:29	0.24	655.4	68.9
Dash8_2	2	Yei (A)	Juba (A)	8 pax r41	8 pax r41	8	22%	8:49	9:03	0.24	655.4	68.9
Dornier_2	1	Juba (A)	Pibor (A)	11 pax r24, 7 pax r25	11 pax r24	18	100%	8:00	8:53	0.89	2110.5	151.2
Dornier_2	2	Pibor (A)	Pochalla (A)	6 pax r35, 3 pax r36	7 pax r25	16	89%	9:13	9:35	0.37	876.6	62.8
Dornier_2	3	Pochalla (A)	Mabior (A)	1 pax r37, 2 pax r38		12	67%	9:55	11:02	0.95	2263.2	162.1
Dornier_2	4	Mabior (A)	Bor (A)	1 pax r30, 5 pax r31	1 pax r30, 6 pax r35, 1 pax r37	18	100%	11:22	11:43	0.36	864.2	61.9
Dornier_2	5	Bor (A)	Juba (A)		5 pax r31, 3 pax r36, 2 pax r38	10	56%	12:03	12:32	0.48	1144.3	82.0
Let_1	1	Juba (A)	Bor (A)	4 pax r13, 6 pax r14		10	59%	8:30	8:58	0.48	1094.1	82.0
Let_1	2	Bor (A)	Malakal (A)			10	59%	9:18	10:31	1.21	2752.9	206.3
Let_1	3	Malakal (A)	Renk (A)		6 pax r14	10	59%	10:51	11:39	0.81	1838.5	137.7
Let_1	4	Renk (A)	Paloich (P)	6 pax r7	4 pax r13	10	59%	11:59	12:22	0.38	857.4	64.2
Let_1	5	Paloich (P)	Juba (A)	1 pax r6	1 pax r6, 6 pax r7	7	41%	12:42	14:45	2.05	4657.3	348.9
Let_2	1	Juba (A)	Boma (A)	1 pax r11, 5 pax r18, 3 pax r24	1 pax r11	9	53%	7:15	8:20	1.09	2732.4	185.2
Let_2	2	Boma (A)	Pibor (A)	3 pax r1	3 pax r24	11	65%	8:40	9:09	0.48	1192.1	80.8
Let_2	3	Pibor (A)	Bor (A)	2 pax r35, 7 pax r36	2 pax r35	17	100%	9:28	10:06	0.62	1547.8	104.9
Let_2	4	Bor (A)	Mabior (A)	2 pax r2	2 pax r2, 5 pax r18	17	100%	10:25	10:47	0.36	913.4	61.9
Let_2	5	Mabior (A)	Juba (A)	2 pax r31	3 pax r1, 2 pax r31, 7 pax r36	12	71%	11:07	11:58	0.85	2122.4	143.9
Let_2	6	Juba (A)	Torit (A)	6 pax r15, 4 pax r19, 1 pax r21	6 pax r15	11	65%	12:37	12:59	0.36	909.1	61.6
Let_2	7	Torit (A)	Mundri (A)	3 pax r8	1 pax r21	8	47%	13:19	14:10	0.85	2130.8	144.4
Let_2	8	Mundri (A)	Maridi (A)		4 pax r19	7	41%	14:30	14:52	0.37	929.6	63.0
Let_2	9	Maridi (A)	Juba (A)	2 pax r32	3 pax r8, 2 pax r32	5	29%	15:12	15:57	0.76	1899.7	128.8
Cessna	1	Juba (A)	Kuajok (A)	9 pax r17	9 pax r17	9	75%	8:45	10:21	1.61	2016.5	299.6
Cessna	2	Kuajok (A)	Juba (A)	12 pax r29	12 pax r29	12	100%	10:41	12:18	1.61	2016.5	299.6
Mi8_2R	1	Rumbek (A)	Jiech (H)	5 pax r16b	5 pax r16b	5	26%	8:15	9:16	1.03	2420.2	123.6
Mi8_2R	2	Jiech (H)	Buot (H)	1 pax r9a		1	5%	9:36	9:40	0.06	152.6	7.8
Mi8_2R	3	Buot (H)	Karmoun (H)	15 pax r4, 3 pax r3a	15 pax r4	19	100%	10:00	10:04	0.08	180.1	9.2
Mi8_2R	4	Karmoun (H)	Rumbek (A)		3 pax r3a, 1 pax r9a	4	21%	10:24	11:27	1.05	2477.8	126.6
Mi8_2R	5	Rumbek (A)	Nyal (H)	5 pax r12b, 1 pax r20b, 2 pax r22b, 1 pax r23b	2 pax r22b	9	47%	11:47	12:20	0.55	1299.6	66.4
Mi8_2R	6	Nyal (H)	Pagil (H)	4 pax r33a	1 pax r23b	11	58%	12:40	13:24	0.73	1724.1	88.1
Mi8_2R	7	Pagil (H)	Mogok (A)	1 pax r34a	1 pax r20b	11	58%	13:43	13:53	0.16	374.2	19.1
Mi8_2R	8	Mogok (A)	Ganyiel (H)		5 pax r12b	10	53%	14:13	14:54	0.69	1629.1	83.2
Mi8_2R	9	Ganyiel (H)	Rumbek (A)	4 pax r5a	4 pax r5a, 4 pax r33a, 1 pax r34a	9	47%	15:14	15:45	0.51	1198.7	61.2
Cessna_1W	1	Wau (A)	Agok (A)	10 pax r10b	10 pax r10b	10	83%	8:45	9:17	0.54	596.9	99.9
Cessna_1W	2	Agok (A)	Wau (A)	8 pax r0a	8 pax r0a	8	67%	9:37	10:09	0.54	596.9	99.9

Table 26 Overview of planned routes for 02-10-2019, resulting from the monthly optimization setting (mgh=60) and 100% demand satisfaction.

aircraft	leg	origin	destination	pick-ups	deliveries	pax on leg	load factor	departure time	arrival time	block time [hr]	leg cost [-]	leg distance [nm]
Dash8Q	1	Juba (A)	Rumbek (A)	1 pax r9a, 8 pax r14a, 4 pax r16a, 10 pax r17a	1 pax r9a, 8 pax r14a, 4 pax r16a, 10 pax r17a	23	32%	7:15	7:49	0.57	3926.5	171.6
Dash8Q	2	Rumbek (A)	Juba (A)			0	0%	8:45	9:19	0.57	3926.5	171.6
Dash8_1	1	Juba (A)	Wau (A)	4 pax r19, 7 pax r22, 3 pax r25a	7 pax r22, 3 pax r25a	14	29%	7:30	8:28	0.97	3212.2	278.3
Dash8_1	2	Wau (A)	Rumbek (A)	7 pax r39, 3 pax r42b	4 pax r19	14	29%	11:04	11:27	0.38	1258.8	109.1
Dash8_1	3	Rumbek (A)	Juba (A)	6 pax r36, 10 pax r32b, 2 pax r33b, 1 pax r34b	6 pax r36, 7 pax r39, 10 pax r32b, 2 pax r33b, 1 pax r34b, 3 pax r42b	29	59%	12:08	12:44	0.60	1980.5	171.6
Dash8_1	4	Juba (A)	Rubkona (A)	10 pax r11, 39 pax r18	39 pax r18	49	100%	13:24	14:24	1.01	3356.7	290.8
Dash8_1	5	Rubkona (A)	Malakal (A)	29 pax r35	10 pax r11	40	82%	14:44	15:07	0.39	1292.9	112.0
Dash8_1	6	Malakal (A)	Juba (A)	19 pax r27	19 pax r27, 29 pax r35	49	100%	15:27	16:27	1.00	3324.7	288.0
Dash8_2	1	Juba (A)	Maban (A)	37 pax r10	37 pax r10	37	100%	9:00	10:09	1.15	3152.4	331.6
Dash8_2	2	Maban (A)	Juba (A)	23 pax r26	23 pax r26	23	62%	10:28	11:37	1.15	3152.4	331.6
Dash8_2	3	Juba (A)	Yambio (A)	19 pax r23, 1 pax r24	19 pax r23	20	54%	12:17	12:57	0.67	1834.1	193.0
Dash8_2	4	Yambio (A)	Yei (A)	9 pax r40	1 pax r24	10	27%	13:17	13:46	0.48	1313.7	138.2
Dash8_2	5	Yei (A)	Juba (A)	1 pax r41	9 pax r40, 1 pax r41	10	27%	14:06	14:20	0.24	655.4	68.9
Mi8_2	1	Juba (A)	Mingkaman (H)	15 pax r6, 3 pax r12	3 pax r12	18	95%	14:34	15:13	0.64	2212.5	76.7
Mi8_2	2	Mingkaman (H)	Bor (A)	1 pax r28, 1 pax r29	15 pax r6, 1 pax r28	17	89%	15:33	15:36	0.05	172.5	6.0
Mi8_2	3	Bor (A)	Juba (A)	9 pax r1	9 pax r1, 1 pax r29	10	53%	15:55	16:36	0.68	2365.6	82.0
Dornier_1	1	Juba (A)	Maban (A)	17 pax r10, 1 pax r21	17 pax r10	18	100%	8:45	10:42	1.95	4629.4	331.6
Dornier_1	2	Maban (A)	Ulang (A)		1 pax r21	1	6%	11:01	11:33	0.53	1256.2	90.0
Dornier_1	3	Ulang (A)	Bor (A)			0	0%	11:53	12:53	1.00	2381.6	170.6
Dornier_1	4	Bor (A)	Juba (A)			0	0%	13:13	13:42	0.48	1144.3	82.0
Dornier_2	1	Juba (A)	Rubkona (A)	11 pax r5, 7 pax r18	7 pax r18	18	100%	8:00	9:42	1.71	4059.0	290.8
Dornier_2	2	Rubkona (A)	Ajuong Thok (A)		11 pax r5	11	61%	10:02	10:20	0.30	717.4	51.4
Dornier_2	3	Ajuong Thok (A)	Bor (A)	12 pax r0		18	100%	10:40	12:04	1.41	3355.0	240.4
Dornier_2	4	Bor (A)	Juba (A)		12 pax r0	18	100%	12:24	12:53	0.48	1144.3	82.0
Dornier_2	5	Juba (A)	Akobo (A)	6 pax r7	6 pax r7	6	33%	13:39	14:48	1.15	2736.7	196.1
Dornier_2	6	Akobo (A)	Juba (A)	11 pax r3	11 pax r3	11	61%	15:07	16:16	1.15	2736.7	196.1
Let_2	1	Juba (A)	Bor (A)	10 pax r8, 7 pax r11		17	100%	7:45	8:13	0.48	1209.4	82.0
Let_2	2	Bor (A)	Malakal (A)		7 pax r11	17	100%	8:33	9:46	1.21	3042.9	206.3
Let_2	3	Malakal (A)	Renk (A)		10 pax r8	10	59%	10:06	10:54	0.81	2032.1	137.7
Let_2	4	Renk (A)	Juba (A)	10 pax r4	10 pax r4	10	59%	11:14	13:40	2.43	6083.4	412.3
Let_2	5	Juba (A)	Nimule (A)	1 pax r15	1 pax r15	1	6%	14:19	14:46	0.44	1111.4	75.3
Let_2	6	Nimule (A)	Juba (A)			0	0%	15:06	15:32	0.44	1111.4	75.3
Cessna	1	Juba (A)	Maban (A)	9 pax r10, 3 pax r13	9 pax r10	12	100%	8:30	10:16	1.78	2232.4	331.6
Cessna	2	Maban (A)	Motot (A)	9 pax r26	3 pax r13	12	100%	10:43	11:29	0.76	957.5	142.2
Cessna	3	Motot (A)	Juba (A)	3 pax r31	9 pax r26, 3 pax r31	12	100%	11:49	12:55	1.10	1376.6	204.5
Cessna	4	Juba (A)	Tambura (A)	3 pax r20	3 pax r20	3	25%	13:54	15:14	1.34	1683.7	250.1
Cessna	5	Tambura (A)	Juba (A)	2 pax r37	2 pax r37	2	17%	15:34	16:54	1.34	1683.7	250.1
Mi8_2	1	Juba (A)	Bor (A)	19 pax r21		19	100%	8:15	8:55	0.68	2365.6	82.0
Mi8_2	2	Bor (A)	Ulang (A)		19 pax r21	19	100%	9:15	10:40	1.42	4923.7	170.6
Mi8_2	3	Ulang (A)	Bor (A)	10 pax r38		10	53%	11:00	12:25	1.42	4923.7	170.6
Mi8_2	4	Bor (A)	Juba (A)		10 pax r38	10	53%	12:45	13:26	0.68	2365.6	82.0
Mi8_1R	1	Rumbek (A)	Nyal (H)	4 pax r16b	4 pax r16b	4	21%	8:30	9:03	0.55	1583.4	66.4
Mi8_1R	2	Nyal (H)	Gorwai (H)	2 pax r33a		2	11%	9:22	9:51	0.48	1385.1	58.1
Mi8_1R	3	Gorwai (H)	Haat (H)	17 pax r2	17 pax r2	19	100%	10:11	10:30	0.32	917.6	38.5
Mi8_1R	4	Haat (H)	Rumbek (A)		2 pax r33a	2	11%	10:50	11:48	0.97	2774.2	116.3
Mi8_2R	1	Rumbek (A)	Old Fangak (A)	1 pax r9b, 8 pax r14b, 10 pax r17b	10 pax r17b	19	100%	8:15	9:31	1.28	2998.2	153.2
Mi8_2R	2	Old Fangak (A)	New Fankgak (A)	1 pax r34a	8 pax r14b	10	53%	9:51	10:00	0.14	334.1	17.1
Mi8_2R	3	New Fankgak (A)	Kurwai (H)	10 pax r32a	1 pax r9b	12	63%	10:19	10:22	0.05	107.4	5.5
Mi8_2R	4	Kurwai (H)	Rumbek (A)		10 pax r32a, 1 pax r34a	11	58%	10:42	12:08	1.43	3351.5	171.2
Cessna_1W	1	Wau (A)	Yida (A)	3 pax r25b	3 pax r25b	3	25%	8:45	9:45	1.00	1110.0	185.8
Cessna_1W	2	Yida (A)	Wau (A)	3 pax r42a	3 pax r42a	3	25%	10:04	11:04	1.00	1110.0	185.8

Table 27 Overview of planned routes for 03-10-2019, resulting from the monthly optimization setting (mgh=60) and 100% demand satisfaction.

aircraft	leg	origin	destination	pick-ups	deliveries	pax on leg	load factor	departure time	arrival time	block time [hr]	leg cost [-]	leg distance [nm]
Dash8Q	1	Juba (A)	Rumbek (A)	7 pax r23, 9 pax r11a, 8 pax r18a, 3 pax r27a	7 pax r23, 9 pax r11a, 8 pax r18a, 3 pax r27a	27	38%	7:30	8:04	0.57	3926.5	171.6
Dash8Q	2	Rumbek (A)	Juba (A)			0	0%	11:01	11:36	0.57	3926.5	171.6
Dash8_1	1	Juba (A)	Wau (A)	6 pax r24, 10 pax r9a, 7 pax r20a	6 pax r24, 10 pax r9a, 7 pax r20a	23	47%	7:45	8:43	0.97	3212.2	278.3
Dash8_1	2	Wau (A)	Rumbek (A)	13 pax r35, 3 pax r0b, 7 pax r31b		23	47%	11:56	12:19	0.38	1258.8	109.1
Dash8_1	3	Rumbek (A)	Juba (A)	15 pax r34, 6 pax r29b, 5 pax r37b	15 pax r34, 13 pax r35, 3 pax r0b, 6 pax r29b, 7 pax r31b, 5 pax r37b	49	100%	12:39	13:15	0.60	1980.5	171.6
Dash8_1	4	Juba (A)	Yei (A)	5 pax r26	5 pax r26	5	10%	13:54	14:09	0.24	795.9	68.9
Dash8_1	5	Yei (A)	Juba (A)	15 pax r36	15 pax r36	15	31%	14:28	14:43	0.24	795.9	68.9
Let_2	1	Juba (A)	Kajo Keji (A)	6 pax r15, 5 pax r17, 5 pax r22	5 pax r17	16	94%	8:00	8:21	0.36	897.8	60.9
Let_2	2	Kajo Keji (A)	Nimule (A)	1 pax r28	5 pax r22	12	71%	8:41	8:49	0.14	359.8	24.4
Let_2	3	Nimule (A)	Torit (A)	3 pax r33	6 pax r15	10	59%	9:09	9:27	0.29	724.4	49.1
Let_2	4	Torit (A)	Juba (A)	13 pax r7	13 pax r7, 1 pax r28, 3 pax r33	17	100%	9:46	10:08	0.36	909.1	61.6
Let_2	5	Juba (A)	Malakal (A)	3 pax r13, 4 pax r14		7	41%	10:48	12:29	1.69	4249.0	288.0
Let_2	6	Malakal (A)	Renk (A)		4 pax r14	7	41%	12:49	13:37	0.81	2032.1	137.7
Let_2	7	Renk (A)	Paloich (P)	9 pax r6	3 pax r13	12	71%	13:57	14:20	0.38	947.7	64.2
Let_2	8	Paloich (P)	Juba (A)	2 pax r5	2 pax r5, 9 pax r6	11	65%	14:40	16:43	2.05	5147.9	348.9
Cessna	1	Juba (A)	Torit (A)			0	0%	7:15	7:34	0.33	414.8	61.6
Cessna	2	Torit (A)	Juba (A)	6 pax r7	6 pax r7	12	100%	7:54	8:14	0.33	414.8	61.6
Cessna	3	Juba (A)	Jikmir (A)	11 pax r16	11 pax r16	11	92%	8:54	10:10	1.27	1593.1	236.7
Cessna	4	Jikmir (A)	Juba (A)	5 pax r8	5 pax r8	12	100%	10:30	11:46	1.27	1593.1	236.7
Cessna	5	Juba (A)	Kuajok (A)	3 pax r19	3 pax r19	3	25%	12:25	14:02	1.61	2016.5	299.6
Cessna	6	Kuajok (A)	Juba (A)	11 pax r30	11 pax r30	11	92%	14:22	15:58	1.61	2016.5	299.6
Dornier_2	1	Juba (A)	Walgal (A)	18 pax r25	18 pax r25	18	100%	8:30	9:43	1.22	2904.4	208.1
Dornier_2	2	Walgal (A)	Juba (A)			0	0%	10:03	11:16	1.22	2904.4	208.1
Dornier_2	3	Juba (A)	Bor (A)	3 pax r10	3 pax r10	3	17%	11:36	12:04	0.48	1144.3	82.0
Dornier_2	4	Bor (A)	Juba (A)	5 pax r2	5 pax r2	5	28%	12:24	12:53	0.48	1144.3	82.0
Mi8_1	1	Juba (A)	Bor (A)	4 pax r12, 9 pax r21		13	68%	8:15	8:55	0.68	1955.1	82.0
Mi8_1	2	Bor (A)	Malakal (A)			13	68%	9:15	10:58	1.72	4919.2	206.3
Mi8_1	3	Malakal (A)	Mathiang (H)		9 pax r21	19	100%	11:18	12:16	0.97	2778.2	116.5
Mi8_1	4	Mathiang (H)	Akobo (A)	2 pax r32	4 pax r12	12	63%	12:36	13:17	0.68	1937.0	81.2
Mi8_1	5	Akobo (A)	Juba (A)	4 pax r4	4 pax r4, 2 pax r32	19	100%	13:37	15:15	1.63	4675.8	196.1
Mi8_1R	1	Rumbek (A)	Dindin (A)	9 pax r11b, 8 pax r18b	9 pax r11b	17	89%	8:30	9:16	0.77	2210.1	92.7
Mi8_1R	2	Dindin (A)	Koch (H)		8 pax r18b	8	42%	9:36	9:48	0.21	600.5	25.2
Mi8_1R	3	Koch (H)	Rumbek (A)	6 pax r29a	6 pax r29a	6	32%	10:08	11:01	0.89	2546.5	106.8
Cessna_1R	1	Rumbek (A)	Yirol (A)	3 pax r27b	3 pax r27b	3	25%	8:15	8:33	0.31	389.5	57.9
Cessna_1R	2	Yirol (A)	Rumbek (A)	5 pax r37a	5 pax r37a	5	42%	8:53	9:12	0.31	389.5	57.9
Cessna_1W	1	Wau (A)	Mankien (A)	7 pax r20b	7 pax r20b	7	58%	8:45	9:18	0.56	617.7	103.4
Cessna_1W	2	Mankien (A)	Wau (A)	7 pax r31a	7 pax r31a	7	58%	9:38	10:12	0.56	617.7	103.4
Cessna_1W	3	Wau (A)	Agok (A)	10 pax r9b	10 pax r9b	10	83%	10:31	11:04	0.54	596.9	99.9
Cessna_1W	4	Agok (A)	Wau (A)	3 pax r0a	3 pax r0a	3	25%	11:24	11:56	0.54	596.9	99.9

Table 28 Overview of planned routes for 04-10-2019, resulting from the monthly optimization setting (mgh=60) and 100% demand satisfaction.

aircraft	leg	origin	destination	pick-ups	deliveries	pax on leg	load factor	departure time	arrival time	block time [hr]	leg cost [-]	leg distance [nm]
Dash8Q	1	Juba (A)	Rumbek (A)	10 pax r11a	10 pax r11a	10	14%	7:15	8:10	0.57	3926.5	171.6
Dash8Q	2	Rumbek (A)	Juba (A)			0	0%	8:30	9:04	0.57	3926.5	171.6
Dash8_1	1	Juba (A)	Malakal (A)	13 pax r8	13 pax r8	13	27%	8:30	9:30	1.00	3324.7	288.0
Dash8_1	2	Malakal (A)	Juba (A)	25 pax r18	25 pax r18	25	51%	9:49	10:49	1.00	3324.7	288.0
Dash8_1	3	Juba (A)	Yei (A)	10 pax r15		10	20%	11:29	11:43	0.24	795.9	68.9
Dash8_1	4	Yei (A)	Yambio (A)	4 pax r26	10 pax r15	14	29%	12:03	12:32	0.48	1595.4	138.2
Dash8_1	5	Yambio (A)	Juba (A)	12 pax r25	12 pax r25, 4 pax r26	16	33%	12:52	13:32	0.67	2227.5	193.0
Dash8_2	1	Juba (A)	Wau (A)	7 pax r16a	7 pax r16a	7	19%	7:30	8:27	0.96	2645.0	278.3
Dash8_2	2	Wau (A)	Juba (A)	9 pax r23, 9 pax r27b	9 pax r23, 9 pax r27b	18	49%	11:04	12:02	0.96	2645.0	278.3
Dash8_2	3	Juba (A)	Rubkona (A)	18 pax r13	18 pax r13	18	49%	12:42	13:42	1.01	2764.0	290.8
Dash8_2	4	Rubkona (A)	Juba (A)	28 pax r22	28 pax r22	28	76%	14:02	15:03	1.01	2764.0	290.8
Dornier_1	1	Juba (A)	Ajuong Thok (A)	12 pax r4	12 pax r4	12	67%	8:15	10:07	1.88	4471.7	320.4
Dornier_1	2	Ajuong Thok (A)	Bor (A)	17 pax r0		17	94%	10:27	11:52	1.41	3355.0	240.4
Dornier_1	3	Bor (A)	Juba (A)		17 pax r0	17	94%	12:12	12:40	0.48	1144.3	82.0
Dornier_2	1	Juba (A)	Bor (A)	10 pax r5	10 pax r5	10	56%	8:00	8:28	0.48	1144.3	82.0
Dornier_2	2	Bor (A)	Juba (A)	8 pax r1, 6 pax r3	8 pax r1	14	78%	8:48	9:17	0.48	1144.3	82.0
Dornier_2	3	Juba (A)	Pibor (A)	9 pax r12	9 pax r12	15	83%	9:37	10:30	0.89	2110.5	151.2
Dornier_2	4	Pibor (A)	Maruw (A)	12 pax r21	6 pax r3	18	100%	10:50	11:12	0.37	885.7	63.5
Dornier_2	5	Maruw (A)	Juba (A)		12 pax r21	18	100%	11:32	12:29	0.95	2247.8	161.0
Mi8_1	1	Juba (A)	Mingkaman (H)	6 pax r5, 1 pax r10, 10 pax r12	1 pax r10	17	89%	7:45	8:23	0.64	1828.5	76.7
Mi8_1	2	Mingkaman (H)	Bor (A)	3 pax r20	6 pax r5	19	100%	8:43	8:46	0.05	142.5	6.0
Mi8_1	3	Bor (A)	Pibor (A)	6 pax r2	10 pax r12	19	100%	9:06	9:58	0.87	2502.2	104.9
Mi8_1	4	Pibor (A)	Labrab (H)		6 pax r2	9	47%	10:18	10:43	0.43	1231.0	51.6
Mi8_1	5	Labrab (H)	Juba (A)		3 pax r20	3	16%	11:03	12:35	1.53	4369.8	183.2
Let_2	1	Juba (A)	Malakal (A)	15 pax r7, 1 pax r14	16	94%	9:00	10:41	1.69	4249.0	288.0	
Let_2	2	Malakal (A)	Maban (A)		15 pax r7	16	94%	11:01	11:45	0.73	1836.3	124.5
Let_2	3	Maban (A)	Udier (A)	7 pax r17	1 pax r14	8	47%	12:04	12:20	0.26	652.1	44.2
Let_2	4	Udier (A)	Mandeng (A)			7	41%	12:40	13:00	0.34	858.2	58.2
Let_2	5	Mandeng (A)	Juba (A)	8 pax r19	7 pax r17, 8 pax r19	15	88%	13:20	14:43	1.39	3494.3	236.9
Mi8_2	1	Juba (A)	Wiechjol LZ (H)	13 pax r7, 3 pax r9		16	84%	8:45	10:26	1.69	5837.0	202.3
Mi8_2	2	Wiechjol LZ (H)	Malakal (A)	3 pax r24		19	100%	10:46	11:34	0.80	2758.2	95.6
Mi8_2	3	Malakal (A)	Maban (A)		13 pax r7	19	100%	11:54	12:56	1.04	3592.0	124.5
Mi8_2	4	Maban (A)	Mathiang (H)	13 pax r17	3 pax r9	19	100%	13:16	13:43	0.46	1597.1	55.3
Mi8_2	5	Mathiang (H)	Juba (A)		13 pax r17, 3 pax r24	16	84%	14:03	16:22	2.31	8001.3	277.3
Mi8_1R	1	Rumbek (A)	Palouny (H)	10 pax r11b	10 pax r11b	10	53%	8:15	9:22	1.13	3243.5	136.0
Mi8_1R	2	Palouny (H)	Rumbek (A)		0	0%	9:42	10:50	1.13	3243.5	136.0	
Cessna_1W	1	Wau (A)	Yida (A)	7 pax r16b	7 pax r16b	7	58%	8:45	9:45	1.00	1110.0	185.8
Cessna_1W	2	Yida (A)	Wau (A)	9 pax r27a	9 pax r27a	12	100%	10:04	11:04	1.00	1110.0	185.8

Table 29 Overview of planned routes for 07-10-2019, resulting from the monthly optimization setting (mgh=60) and 100% demand satisfaction.

aircraft	leg	origin	destination	pick-ups	deliveries	pax on leg	load factor	departure time	arrival time	block time [hr]	leg cost [-]	leg distance [nm]
Dash8Q	1	Juba (A)	Rumbek (A)	13 pax r20, 16 pax r21, 6 pax r8a, 14 pax r12a, 3 pax r15a, 6 pax r16a	13 pax r20, 6 pax r8a, 14 pax r12a, 3 pax r15a, 6 pax r16a	58	82%	7:30	8:04	0.57	3926.5	171.6
Dash8Q	2	Rumbek (A)	Wau (A)	5 pax r1b, 6 pax r24b, 4 pax r25b	16 pax r21	31	44%	13:50	14:12	0.36	2495.8	109.1
Dash8Q	3	Wau (A)	Juba (A)	19 pax r34, 7 pax r0b, 5 pax r28b, 10 pax r38b	19 pax r34, 7 pax r0b, 5 pax r1b, 6 pax r24b, 4 pax r25b, 5 pax r28b, 10 pax r38b	56	79%	15:35	16:31	0.93	6368.7	278.3
Dash8_1	1	Juba (A)	Maban (A)	26 pax r13, 23 pax r14	26 pax r13	49	100%	8:30	9:39	1.16	3828.4	331.6
Dash8_1	2	Maban (A)	Malakal (A)	16 pax r26	23 pax r14	39	80%	9:59	10:25	0.43	1436.8	124.5
Dash8_1	3	Malakal (A)	Juba (A)	24 pax r27	16 pax r26, 24 pax r27	49	100%	10:45	11:45	1.00	3324.7	288.0
Dash8_2	1	Juba (A)	Wau (A)	22 pax r9, 4 pax r7a, 4 pax r18a, 4 pax r23a	4 pax r7a, 4 pax r18a, 4 pax r23a	34	92%	7:15	8:12	0.96	2645.0	278.3
Dash8_2	2	Wau (A)	Aweil (A)		22 pax r9	22	59%	9:00	9:15	0.25	685.4	72.1
Dash8_2	3	Aweil (A)	Rumbek (A)	19 pax r2		19	51%	9:34	10:11	0.61	1675.3	176.2
Dash8_2	4	Rumbek (A)	Juba (A)	14 pax r33, 2 pax r30b	19 pax r2, 14 pax r33, 2 pax r30b	35	95%	10:31	11:06	0.59	1630.8	171.6
Dash8_2	5	Juba (A)	Rubkona (A)	35 pax r19	35 pax r19	35	95%	11:46	12:46	1.01	2764.0	290.8
Dash8_2	6	Rubkona (A)	Juba (A)	12 pax r32	12 pax r32	12	32%	13:06	14:07	1.01	2764.0	290.8
Dash8_2	7	Juba (A)	Yambio (A)	16 pax r22	16 pax r22	16	43%	14:46	15:27	0.67	1834.1	193.0
Dash8_2	8	Yambio (A)	Juba (A)	25 pax r37	25 pax r37	25	68%	15:46	16:27	0.67	1834.1	193.0
Let_1	1	Juba (A)	Akobo (A)	15 pax r11	15 pax r11	15	88%	8:15	9:24	1.15	2616.7	196.1
Let_1	2	Akobo (A)	Juba (A)	8 pax r6	8 pax r6	8	47%	9:43	10:52	1.15	2616.7	196.1
Cessna	1	Juba (A)	Bor (A)	6 pax r10	6 pax r10	6	50%	8:00	8:26	0.44	551.8	82.0
Cessna	2	Bor (A)	Rumbek (A)	1 pax r4a	1 pax r4a	1	8%	8:46	9:25	0.65	819.1	121.7
Cessna	3	Rumbek (A)	Juba (A)			0	0%	9:45	10:40	0.92	1154.8	171.6
Cessna	4	Juba (A)	Akobo (A)	3 pax r11, 7 pax r14, 2 pax r17	3 pax r11	12	100%	11:19	12:22	1.05	1319.7	196.1
Cessna	5	Akobo (A)	Malakal (A)		7 pax r14	12	100%	12:42	13:25	0.72	907.5	134.8
Cessna	6	Malakal (A)	Pieri (A)		2 pax r17	5	42%	13:45	14:18	0.54	678.8	100.8
Cessna	7	Pieri (A)	Juba (A)			3	25%	14:37	15:40	1.04	1298.8	193.0
Mi8_2	1	Juba (A)	Mingkaman (H)	17 pax r10		17	89%	7:45	8:23	0.64	2212.5	76.7
Mi8_2	2	Mingkaman (H)	Bor (A)	2 pax r29	17 pax r10	19	100%	8:43	8:46	0.05	172.5	6.0
Mi8_2	3	Bor (A)	Juba (A)	13 pax r3	13 pax r3, 2 pax r29	15	79%	9:06	9:46	0.68	2365.6	82.0
Mi8_1R	1	Rumbek (A)	Koch (H)			0	0%	7:15	8:08	0.89	2546.5	106.8
Mi8_1R	2	Koch (H)	Padeah (H)	6 pax r24a		6	32%	8:28	8:34	0.11	302.4	12.7
Mi8_1R	3	Padeah (H)	Rumbek (A)	2 pax r30a	6 pax r24a, 2 pax r30a	8	42%	8:54	9:43	0.82	2335.0	97.9
Mi8_1R	4	Rumbek (A)	Lankien (H)	1 pax r4b, 14 pax r12b, 3 pax r15b	1 pax r4b, 14 pax r12b	18	95%	10:15	11:41	1.44	4135.4	173.4
Mi8_1R	5	Lankien (H)	Mogok (A)	4 pax r25a	3 pax r15b	7	37%	12:01	12:18	0.29	819.3	34.4
Mi8_1R	6	Mogok (A)	Rumbek (A)		4 pax r25a	4	21%	12:38	13:50	1.20	3428.9	143.8
Cessna_1R	1	Rumbek (A)	Ajuong Thok (A)	6 pax r8b, 6 pax r16b	6 pax r8b	12	100%	8:15	9:16	1.03	1287.7	191.3
Cessna_1R	2	Ajuong Thok (A)	New Fankgak (A)	5 pax r1a	6 pax r16b	11	92%	9:36	9:57	0.34	425.5	63.2
Cessna_1R	3	New Fankgak (A)	Rumbek (A)		5 pax r1a	12	100%	10:16	11:12	0.92	1145.8	170.2
Cessna_1W	1	Wau (A)	Raja (A)	5 pax r35, 4 pax r18b	5 pax r35, 4 pax r18b	9	75%	8:45	9:31	0.77	860.5	144.1
Cessna_1W	2	Raja (A)	Wau (A)	9 pax r31	9 pax r31	9	75%	9:51	10:37	0.77	860.5	144.1
Cessna_1W	3	Wau (A)	Yida (A)	4 pax r23b	4 pax r23b	4	33%	10:57	11:57	1.00	1110.0	185.8
Cessna_1W	4	Yida (A)	Wau (A)	10 pax r38a	10 pax r38a	10	83%	12:16	13:16	1.00	1110.0	185.8
Cessna_1W	5	Wau (A)	Agok (A)	4 pax r7b	4 pax r7b	4	33%	13:36	14:09	0.54	596.9	99.9
Cessna_1W	6	Agok (A)	Mankien (A)	7 pax r0a		7	58%	14:28	14:42	0.22	243.8	40.8
Cessna_1W	7	Mankien (A)	Wau (A)	5 pax r28a	7 pax r0a, 5 pax r28a	12	100%	15:01	15:35	0.56	617.7	103.4

Table 30 Overview of planned routes for 08-10-2019, resulting from the monthly optimization setting (mgh=60) and 100% demand satisfaction.

aircraft	leg	origin	destination	pick-ups	deliveries	pax on leg	load factor	departure time	arrival time	block time [hr]	leg cost [-]	leg distance [nm]
Dash8Q	1	Juba (A)	Wau (A)	10 pax r22, 12 pax r23, 2 pax r9a	12 pax r23, 2 pax r9a	24	34%	7:30	8:25	0.93	6368.7	278.3
Dash8Q	2	Wau (A)	Rumbek (A)	11 pax r34	10 pax r22	21	30%	9:00	9:21	0.36	2495.8	109.1
Dash8Q	3	Rumbek (A)	Juba (A)	4 pax r33, 3 pax r28b	4 pax r33, 11 pax r34, 3 pax r28b	18	25%	9:41	10:15	0.57	3926.5	171.6
Dash8_2	1	Juba (A)	Rumbek (A)	19 pax r10, 4 pax r13a, 4 pax r14a, 4 pax r19a	4 pax r13a, 4 pax r14a, 4 pax r19a	31	84%	7:15	7:50	0.59	1630.8	171.6
Dash8_2	2	Rumbek (A)	Aweil (A)	4 pax r6b, 3 pax r7b, 3 pax r8b, 7 pax r30b	19 pax r10	36	97%	11:44	12:21	0.61	1675.3	176.2
Dash8_2	3	Aweil (A)	Wau (A)	18 pax r1, 1 pax r2	1 pax r2	36	97%	12:40	12:55	0.25	685.4	72.1
Dash8_2	4	Wau (A)	Juba (A)	2 pax r0b	18 pax r1, 2 pax r0b, 4 pax r6b, 3 pax r7b, 3 pax r8b, 7 pax r30b	37	100%	13:15	14:13	0.96	2645.0	278.3
Dash8_2	5	Juba (A)	Yei (A)	18 pax r24	18 pax r24	18	49%	14:52	15:07	0.24	655.4	68.9
Dash8_2	6	Yei (A)	Juba (A)	9 pax r35, 9 pax r36	9 pax r35, 9 pax r36	18	49%	15:27	15:41	0.24	655.4	68.9
Dornier_1	1	Juba (A)	Kuajok (A)	15 pax r16	15 pax r16	15	83%	8:30	10:15	1.76	4181.7	299.6
Dornier_1	2	Kuajok (A)	Juba (A)	5 pax r26	5 pax r26	5	28%	10:35	12:21	1.76	4181.7	299.6
Dornier_2	1	Juba (A)	Bor (A)	8 pax r11, 1 pax r12, 5 pax r21	1 pax r12	14	78%	8:15	8:43	0.48	1144.3	82.0
Dornier_2	2	Bor (A)	Boma (A)	4 pax r4, 1 pax r5	8 pax r11	18	100%	9:03	10:03	1.00	2379.2	170.4
Dornier_2	3	Boma (A)	Pochalla (A)	1 pax r3	1 pax r5, 5 pax r21	11	61%	10:23	10:45	0.36	857.2	61.4
Dornier_2	4	Pochalla (A)	Pibor (A)	2 pax r32	4 pax r4	7	39%	11:04	11:27	0.37	876.6	62.8
Dornier_2	5	Pibor (A)	Juba (A)	13 pax r31	1 pax r3, 13 pax r31, 2 pax r32	16	89%	11:46	12:40	0.89	2110.5	151.2
Let_1	1	Juba (A)	Pibor (A)	14 pax r20	14 pax r20	14	82%	8:00	8:53	0.89	2018.0	151.2
Let_1	2	Pibor (A)	Juba (A)			0	0%	9:13	10:06	0.89	2018.0	151.2
Cessna	1	Juba (A)	Maridi (A)	2 pax r17, 2 pax r18	2 pax r17	4	33%	7:45	8:26	0.69	866.7	128.8
Cessna	2	Maridi (A)	Mundri (A)	2 pax r27	2 pax r18	4	33%	8:46	9:06	0.34	424.1	63.0
Cessna	3	Mundri (A)	Juba (A)	1 pax r29	2 pax r27, 1 pax r29	3	25%	9:26	9:53	0.45	558.2	82.9
Cessna	4	Juba (A)	Kapoeta (A)	10 pax r15	10 pax r15	10	83%	10:13	10:52	0.66	823.2	122.3
Cessna	5	Kapoeta (A)	Juba (A)	6 pax r25	6 pax r25	6	50%	11:12	11:52	0.66	823.2	122.3
Mi8_2R	1	Rumbek (A)	Ganyiel (H)	4 pax r13b, 4 pax r14b, 4 pax r19b	4 pax r13b	12	63%	8:15	8:45	0.51	1198.7	61.2
Mi8_2R	2	Ganyiel (H)	Gorwai (H)	4 pax r6a		12	63%	9:05	9:34	0.49	1153.6	58.9
Mi8_2R	3	Gorwai (H)	Jiech (H)	3 pax r7a	4 pax r14b	15	79%	9:54	10:02	0.13	294.6	15.1
Mi8_2R	4	Jiech (H)	Nyal (H)	3 pax r8a	4 pax r19b	14	74%	10:22	10:51	0.49	1143.7	58.4
Mi8_2R	5	Nyal (H)	Rumbek (A)	7 pax r30a	4 pax r6a, 3 pax r7a, 3 pax r8a, 7 pax r30a	17	89%	11:11	11:44	0.55	1299.6	66.4
Cessna_1R	1	Rumbek (A)	Mogok (A)			0	0%	7:15	8:01	0.77	967.7	143.8
Cessna_1R	2	Mogok (A)	Rumbek (A)	3 pax r28a	3 pax r28a	3	25%	8:21	9:07	0.77	967.7	143.8
Cessna_1W	1	Wau (A)	Alek (A)	2 pax r9b	2 pax r9b	2	17%	8:45	9:03	0.31	341.4	57.1
Cessna_1W	2	Alek (A)	Wau (A)	2 pax r0a	2 pax r0a	2	17%	9:23	9:42	0.31	341.4	57.1

F. Results 2015

This section presents the results from the model for the 2015 data set and also shows the results from the reference model (HFOM from [19]) and two human flight planners.

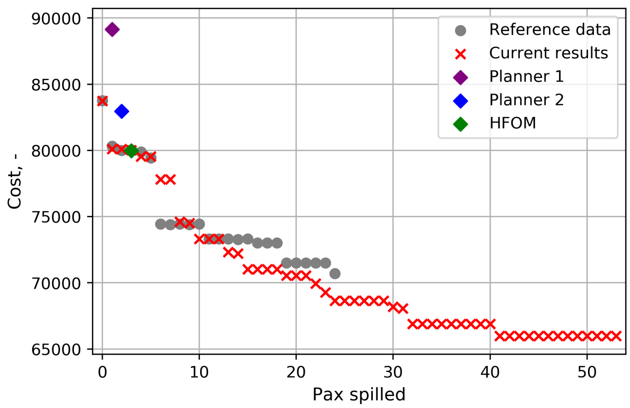

Fig. 33 Comparison of the results for 13-04-2015 made by the current model, two human flight planners and the reference model (HFOM). The grey points (reference data) correspond to the Pareto front created in [19] for validation.

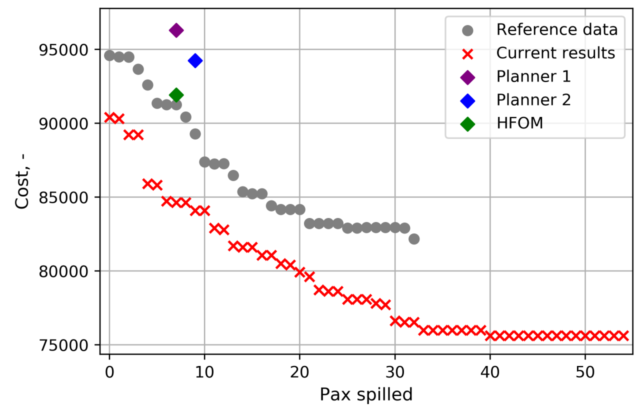

Fig. 34 Comparison of the results for 14-04-2015 made by the current model, two human flight planners and the reference model (HFOM). The grey points (reference data) correspond to the Pareto front created in [19] for validation.

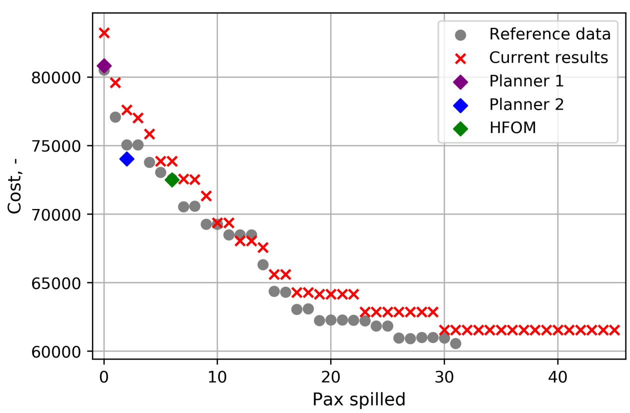

Fig. 35 Comparison of the results for 15-04-2015 made by the current model, two human flight planners and the reference model (HFOM). The grey points (reference data) correspond to the Pareto front created in [19] for validation.

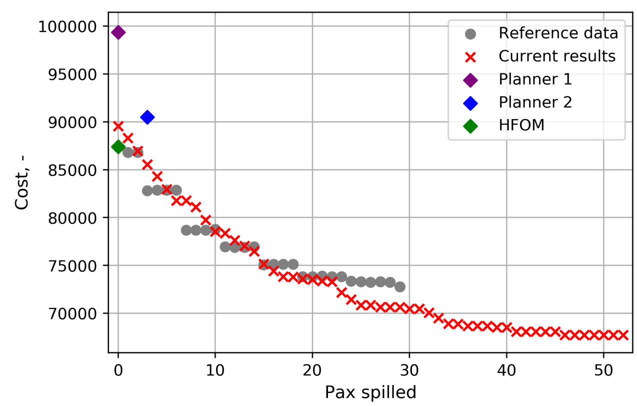

Fig. 36 Comparison of the results for 16-04-2015 made by the current model, two human flight planners and the reference model (HFOM). The grey points (reference data) correspond to the Pareto front created in [19] for validation.

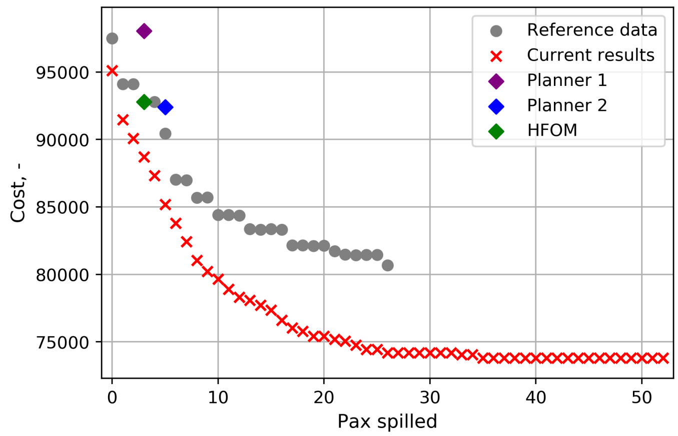

Fig. 37 Comparison of the results for 17-04-2015 made by the current model, two human flight planners and the reference model (HFOM). The grey points (reference data) correspond to the Pareto front created in [19] for validation.

G. Verification

In order to verify the behavior of the model, nine very straightforward test cases were executed. The expected outcome of these scenarios are obvious, making it easy to verify all important aspects of the model.

The verification scenarios are all based on the same, simple data set. It consists of 3 airports, A, B, and C, with relevant information given in Table 31. A visual overview of the locations can be found in Figure 38. Airport A is the base for the the two aircraft AC1 and AC2 as described in Table 32. Both aircraft have a turn around time of 0.25 time units for all airports.

Table 31 Fictive, unitless, airport data for the verification process.

Name	Coordinates	Runway
A	(0,0)	3000
B	(0,1)	1000
C	(0,2)	3000

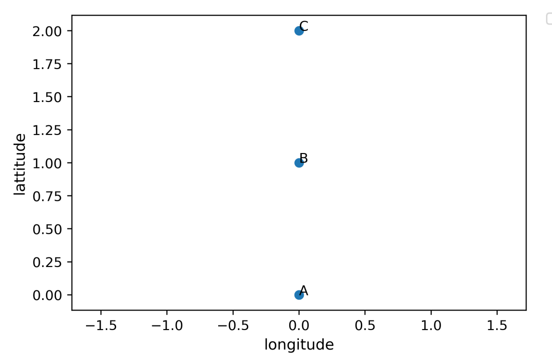

Fig. 38 Locations of the verification airports.

Table 32 Fictive, unitless, fleet data for the verification process. The costs are the costs per distance unit.

Name	Speed	Cost	Base	Seats	Range	Runway required
AC1	0.5	5	A	2	3	1000
AC2	0.5	4	A	4	4	3000

Nine scenarios were developed and can be found in Table 33. In the following paragraphs the outcomes of these scenarios will be discussed.

Table 33 Overview of the different scenarios.

Scenario	Fleet	Time limitations	Refueling
1	AC1	Back at hub at t=10	-
2	AC1	Back at hub at t=10	-
3	AC1	Back at hub at t=10	B
4	AC1	Back at hub at t=8.25	B
5	AC1, AC2	Back at hub at t=10	B
6	AC1, AC2	Back at hub at t=10	B
7	AC1, AC2	Back at hub at t=8.25	B
8	AC1, AC2	Back at hub at t=8.25 AC1 used till t=1	B
9	AC1, AC2	Back at hub at t=10 Deliver r0 before t=5 Pick-up r1 after t=4.5	B

Table 34 Requests for the different verification scenarios.

Scenario	Request	From	To	Count
1	0	A	B	2
	1	B	A	3
2, 3, 4, 6, 7 and 8	0	A	B	1
	1	C	A	1
5	0	A	B	1
	1	B	A	1
9	0	B	A	1
	1	C	A	1

Table 35 Computed flight routes by the model based on the verification cases.

Scenario	AC	Leg	O	D	Pax on leg	Pax on	Pax off	Departure time	Arrival time	Block time	Leg cost	Leg dist
1	AC1	1	A	B	2	2p r0	2p r0	0	2	2	5	1
	AC1	2	B	A	2	2p r1	2p r1	2.25	4.25	2	5	1
2	AC1	1	A	B	1	1p r0	1p r0	0	2	2	5	1
	AC1	2	B	A	0			2.25	4.25	2	5	1
3	AC1	1	A	C	1	1p r0		0	4	4	10	2
	AC1	2	C	B	2	1p r1	1p r0	4.25	6.25	2	5	1
	AC1	3	B	A	1		1p r1	6.5	8.5	2	5	1
4	AC1	1	A	B	1	1p r0	1p r0	0	2	2	5	1
	AC1	2	B	A	0			2.25	4.25	2	5	1
5	AC1	1	A	B	1	1p r0	1p r0	0	2	2	5	1
	AC1	2	B	A	1	1p r1	1p r1	2.25	4.25	2	5	1
6	AC1	1	A	B	1	1p r0	1p r0	0	2	2	5	1
	AC1	2	B	C	0			2.25	4.25	2	5	1
	AC1	3	C	A	1	1p r1	1p r1	4.5	8.5	4	10	2
7	AC1	1	A	B	1	1p r0	1p r0	0.25	2.25	2	5	1
	AC1	2	B	A	0			2.5	4.5	2	5	1
	AC2	1	A	C	0			0	4	4	8	2
	AC2	2	C	A	1	1p r1	1p r1	4.25	8.25	4	8	2
8	AC1	1	A	B	1	1p r0	1p r0	1.25	3.25	2	5	1
	AC1	2	B	A	0			3.5	5.5	2	5	1
	AC2	1	A	C	0			0	4	4	8	2
	AC2	2	C	A	1	1p r1	1p r1	4.25	8.25	4	8	2
9	AC1	1	A	B	0			0	2	2	5	1
	AC1	2	B	A	1	1p r0	1p r0	2.25	4.25	2	5	1
	AC2	1	A	C	0			0.25	4.75	4	8	2
	AC2	2	C	A	1	1p r1	1p r1	5	9	4	8	2

1) Load and capacity

The first scenario is focused on checking the load constraints (Constraints 12 and 13). Since the amount of request 1 is larger than the capacity of AC1 (the only available aircraft) it is expected that a passenger will be spilled. This is verified in Table 35, where it can be seen that only 2 of the 3 passengers are transported.

2) Range

Secondly, the range constraints (constraints 21 and 23) are verified. Table 34 shows a request from airport C to A. However, airport C is at a distance of 2 from the hub, making it too far for a round way trip for AC1, which has a range of 3. Therefore, it is expected that this request will be fully spilled. This is indeed what happens, as can be seen in Table 35.

3) Refuelling

This scenario extends on scenario 2. In scenario 2, airport C was out of range. However, in this scenario airport B is added as a refuelling station (see Constraint 22). Therefore, it is expected that the request from airport C is transported, using B as a fuel stop. Indeed, this is exactly what happens, as can be found in Table 35.

4) End time

For this scenario the previous scenario is further adapted by limiting the end time. Now the aircraft has to be back at the hub after 8.25 time units. The solution found for scenario 3 takes 8.5 time units. It is therefore expected that this route is not feasible anymore, and that the passengers from airport C are spilled. Looking at Table 35, this is exactly what happens.

5) Required runway

A second aircraft is added to the fleet for this scenario. This aircraft (AC2) has a lower cost per distant unit than AC1. Its usage should therefore be preferred over the usage of AC1. However, AC2 requires a runway of 3,000m, and airport B has a runway of 1,000m. The expected aircraft to transport this request is therefore AC1. This outcome can be verified in Table 35.

6) Aircraft cost

To further check if the model chooses the right aircraft from the heterogeneous fleet, scenario 6 was constructed. A passenger needs to be transported from airport C. Since AC2 can land on this airport and is cheaper than AC1, it makes it a logical aircraft to transport this request. However, AC1 is already at airport B to transport request 0. It is cheaper for AC1 to fly a bit further to airport C, than for AC2 to fly to airport C from airport A. The expected outcome would therefore not include AC2. As shown in Table 35, the outcome is as expected.

7) Take-off difference

Scenario 7 verifies if the take-off time difference is adhered to, as described in Constraints 19 and 20. The end time is lowered again to 8.25 time units. This makes the route for AC1 to airport C infeasible, as shown in scenario 4. This means both aircraft will be utilized. The aircraft should depart with a time difference of at least 0.25 time units. Table 35 shows that this is the case.

8) Fleet availability

Scenario 8 deals with the case where an aircraft is not fully available, because it is already used in another region. In this case AC1 is used up to 1 time unit. The aircraft should therefore depart at t=1.25, because the turn around time must also be respected. This is verified by looking at Table 35.

9) Transit passengers

To accommodate transit passengers, some requests need to be delivered before a certain time (if the request corresponds to the first half of the itinerary), or picked-up after a certain time (corresponding to the second half of the itinerary). In this case request 0 needs to be delivered before t=5, and request 1 needs to be picked up after t=4.5. The results as shown in Table 35 verify that both time limits are adhered to.

Furthermore it can be seen that in all scenarios the departure times, arrival times, block times, leg cost, and leg distance correspond to the expected values based on Table 31 and 32. Also the vehicle flow (constraint 3) is respected and the aircraft start and end at the base airport. It is also evident that for each request the pick-up and delivery are performed by the same vehicle and pick-ups take place before delivery.

Based on the results of these nine verification scenarios it is evident that the model behaves as expected and adheres to all constraints.

H. Pareto front creation verification

Figures 39 till 49 compare the created Pareto fronts to the verification reruns.

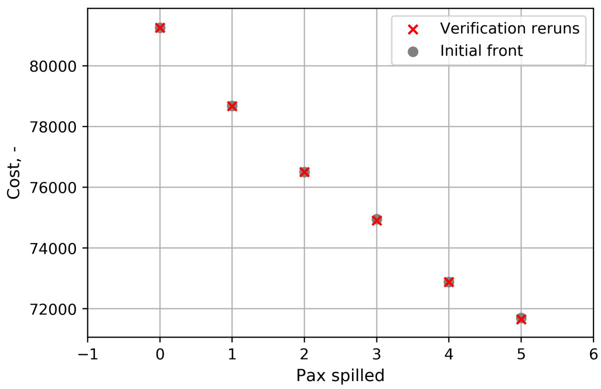

Fig. 39 Comparison of the Pareto front 24-09-2019 made by the current model (daily optimization) and the separate reruns.

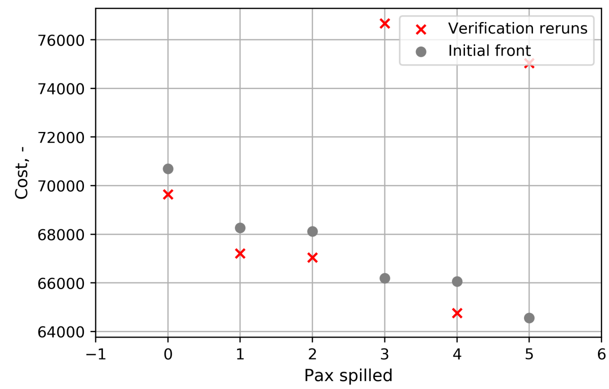

Fig. 40 Comparison of the Pareto front 25-09-2019 made by the current model (daily optimization) and the separate reruns.

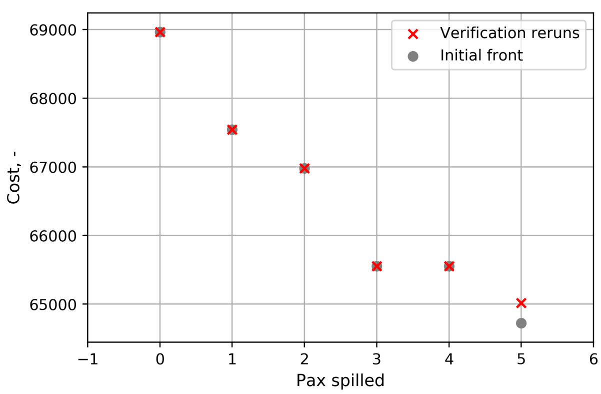

Fig. 41 Comparison of the Pareto front 26-09-2019 made by the current model (daily optimization) and the separate reruns.

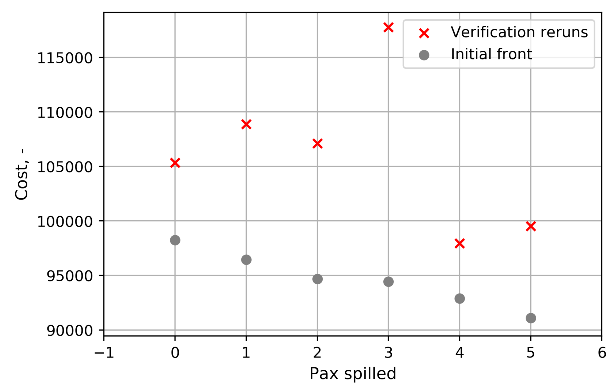

Fig. 42 Comparison of the Pareto front 27-09-2019 made by the current model (daily optimization) and the separate reruns.

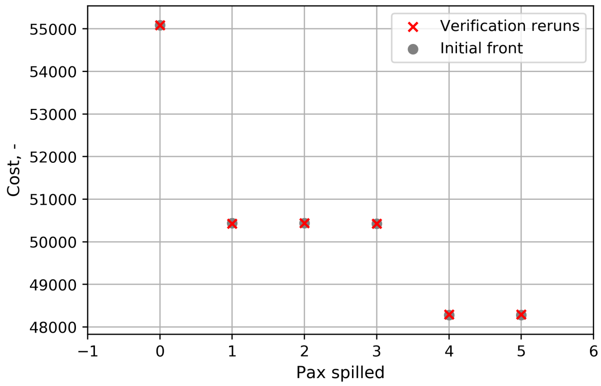

Fig. 43 Comparison of the Pareto front 30-09-2019 made by the current model (daily optimization) and the separate reruns.

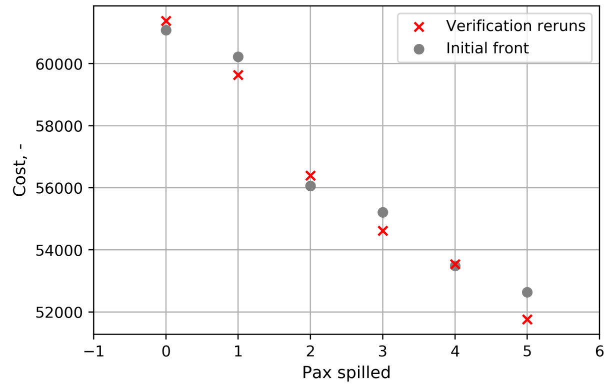

Fig. 44 Comparison of the Pareto front 01-10-2019 made by the current model (daily optimization) and the separate reruns.

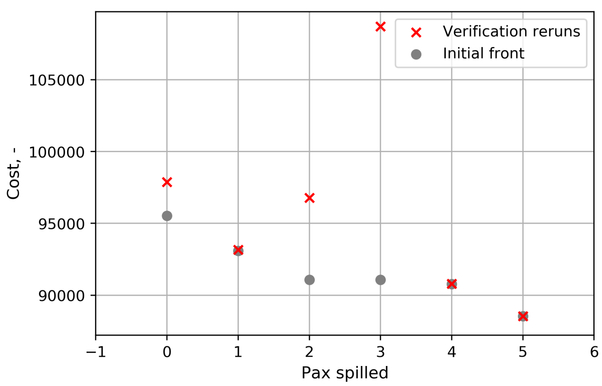

Fig. 45 Comparison of the Pareto front 02-10-2019 made by the current model (daily optimization) and the separate reruns.

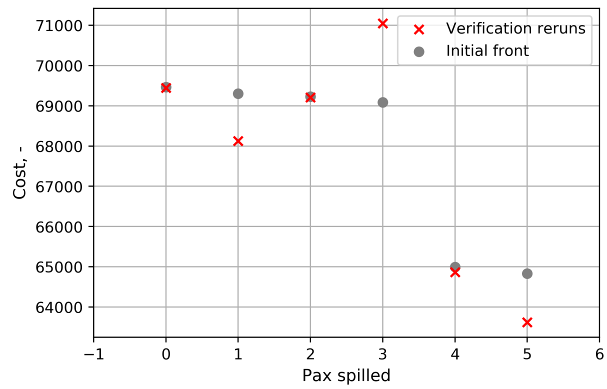

Fig. 46 Comparison of the Pareto front 03-10-2019 made by the current model (daily optimization) and the separate reruns.

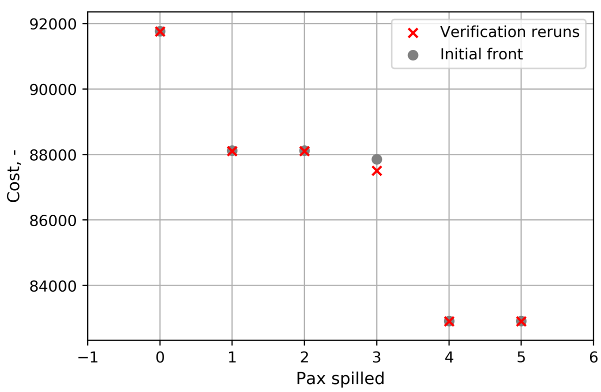

Fig. 47 Comparison of the Pareto front 04-10-2019 made by the current model (daily optimization) and the separate reruns.

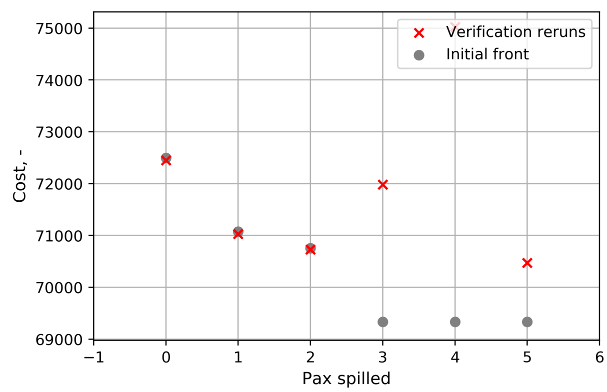

Fig. 48 Comparison of the Pareto front 07-10-2019 made by the current model (daily optimization) and the separate reruns.

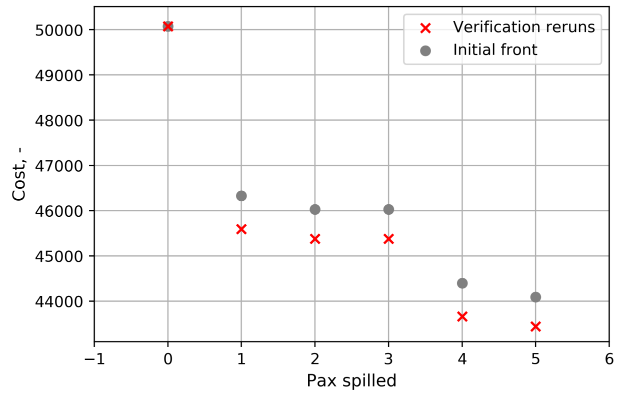

Fig. 49 Comparison of the Pareto front 08-10-2019 made by the current model (daily optimization) and the separate reruns.

I. Cumulated flight hours

Corresponding to Section VII.C.1, Figure 50 and 51 show the cumulated flight hours per aircraft when optimizing for 50 and 42 minimum guaranteed hours, respectively.

Figure 52 and 53 show the cumulated flight hours as a result of running the model with alternative pricing scheme 1 and 2, respectively. These figures correspond to the analysis described in Section VII.C.2.

In line with Section VII.C.4 Figure 54 shows the cumulated flight hours for 100% demand satisfaction, resulting from running the adapted model in monthly optimization mode for 60 minimum guaranteed hours.

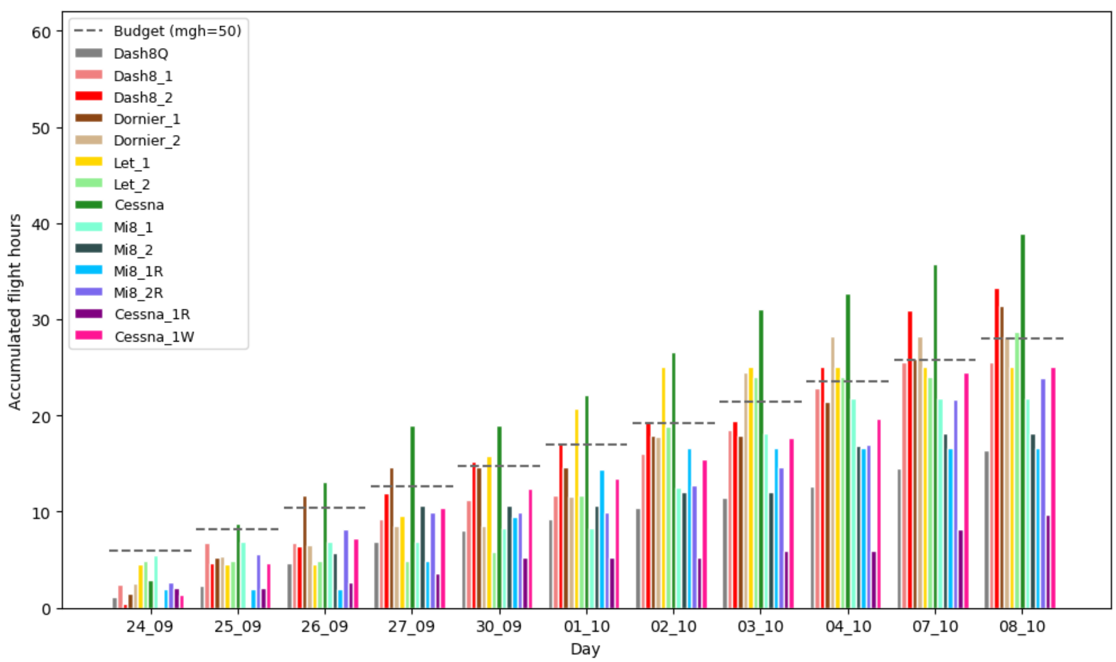

Fig. 50 Accumulated flight hours per aircraft. Monthly optimization (mgh=50) and 100% demand satisfaction.

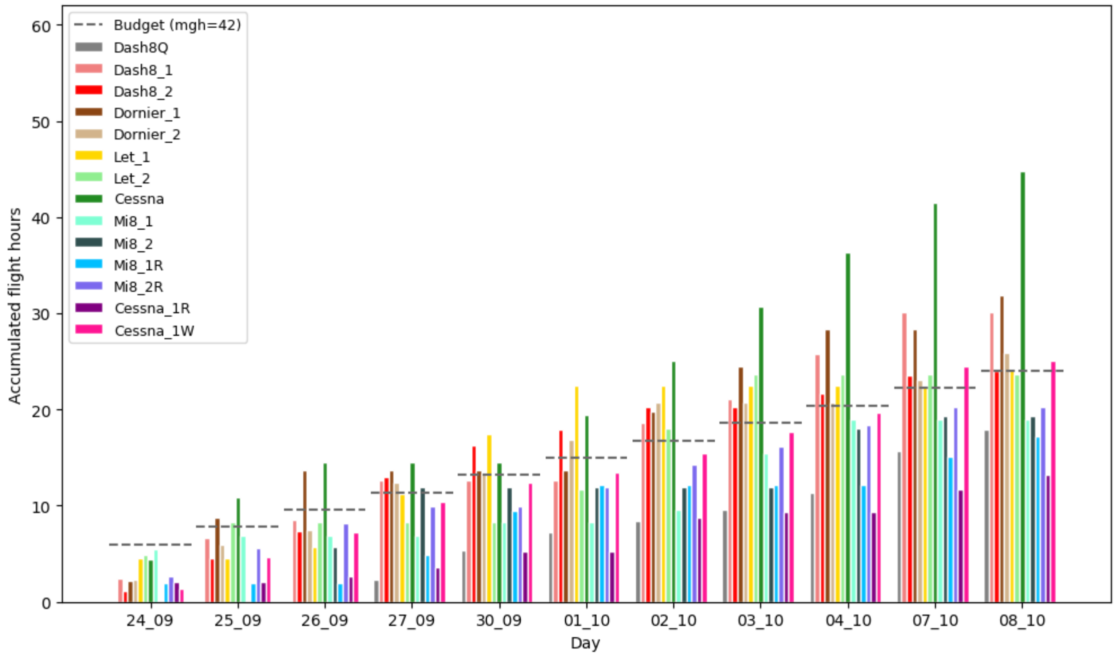

Fig. 51 Accumulated flight hours per aircraft. Monthly optimization (mgh=42) and 100% demand satisfaction.

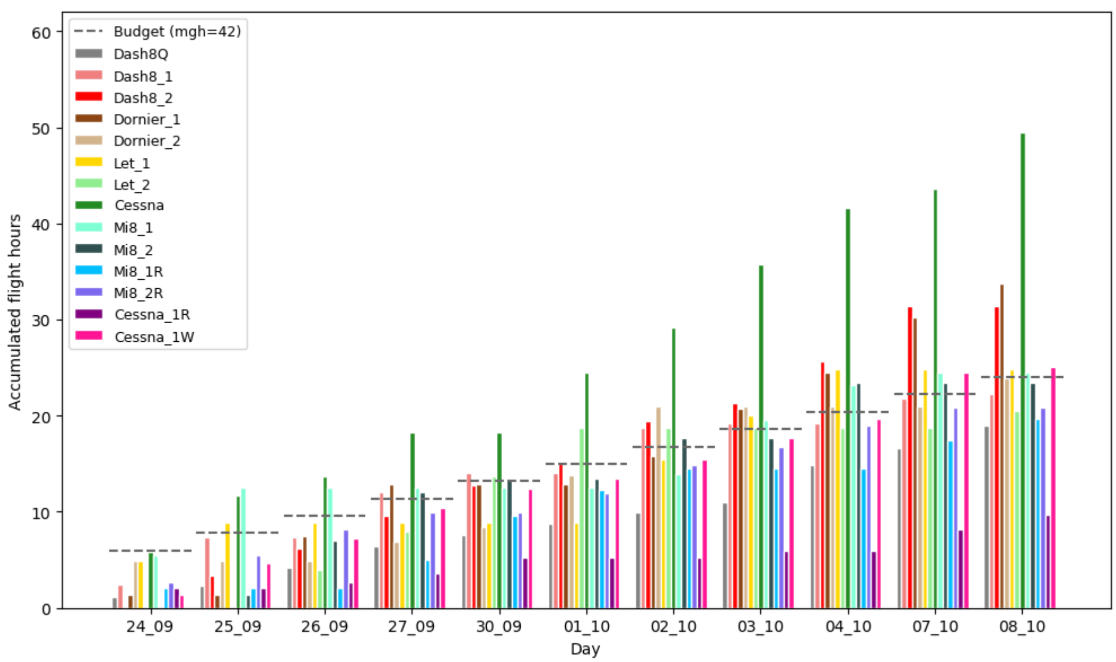

Fig. 52 Accumulated flight hours per aircraft. Monthly optimization (mgh=42), alternative pricing scheme 1 (Fig. 7) and 100% demand satisfaction.

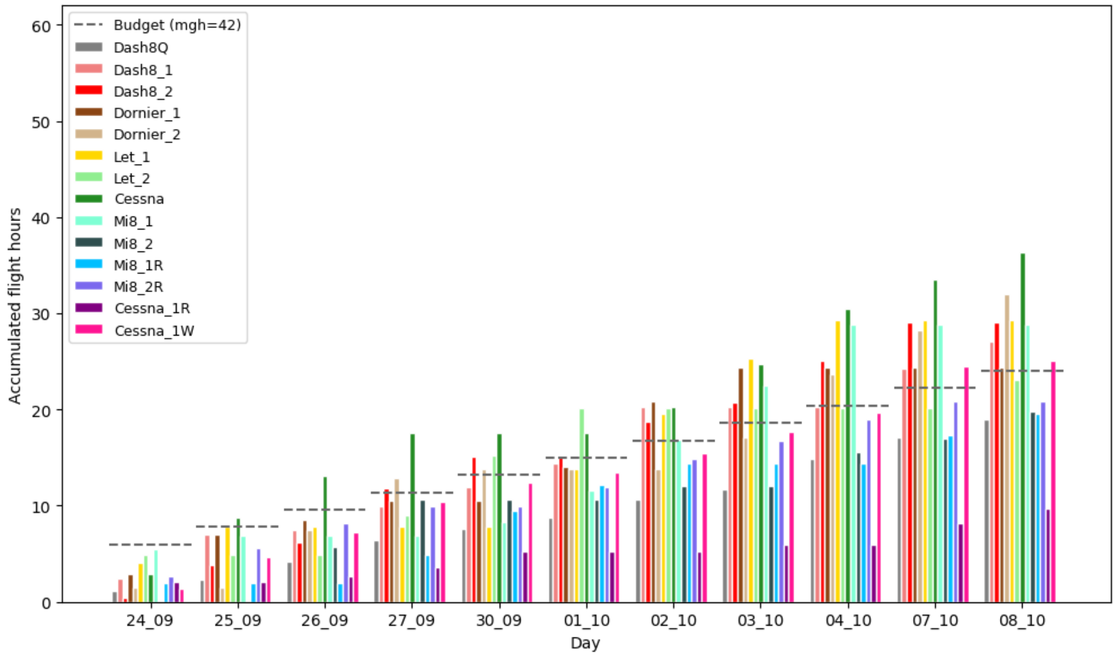

Fig. 53 Accumulated flight hours per aircraft. Monthly optimization (mgh=42), alternative pricing scheme 2 (Fig. 8) and 100% demand satisfaction.

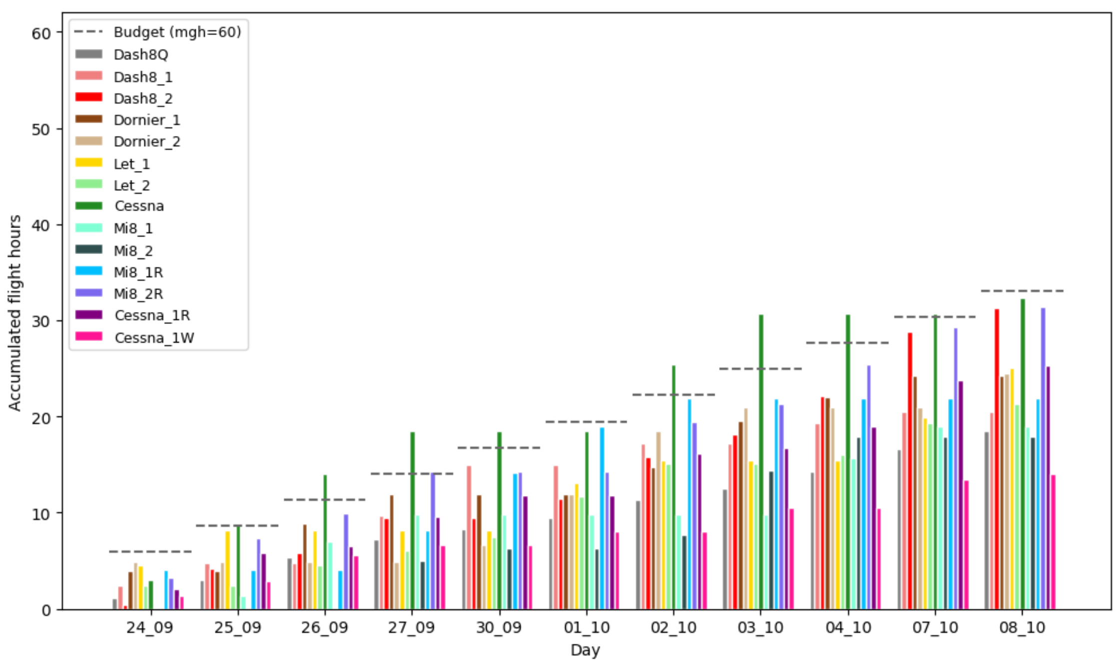

Fig. 54 Accumulated flight hours per aircraft resulting from the adapted model. Monthly optimization (mgh=60) and 100% demand satisfaction.

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